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Design and development of basic physical layer WiMAX network simulation models

Final contract report

Bob Szeker

Defence R&D Canada – Ottawa

CONTRACT REPORT

DRDC Ottawa CR 2008-296

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Design and development of basic physical layer WiMAX network simulation models

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Contract Report

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Abstract

This report details and summarizes the work performed in developing computer simulation models for fixed and mobile WiMAX physical layers. The development was divided into 3 phases during which various simulation models of increasing complexity were produced. The models were coded using Matlab software. Emphasis was placed on developing source code in strict accordance with WiMAX standard specifications.

The initial software models simulated a fixed WiMAX physical layer during which key concepts and technologies were investigated. The software models developed during the last phase provided a partial simulation of a mobile WiMAX physical layer. An excellent understanding was gained of mobile WiMAX technology and its limitations in a simulated environment. Simulations showed that the performance of the WiMAX physical layer is dependent strongly on the propagation channel through which the RF signals propagate.

Résumé

Ce rapport explique et résume le travail accompli dans le développement de modèles de simulation par ordinateur de la couche physique de la technologie fixe et mobile WiMAX. Le développement a été divisé en 3 phases au cours desquelles différents modèles de simulation de plus en plus complexes ont été produits. Les modèles ont été codés en utilisant le logiciel Matlab. L'accent a été mis sur le développement de code source suivant le strict respect des requis de la norme WiMAX.

Les modèles logiciels initiaux ont servi à effectuer une simulation de la couche physique WiMAX fixe au cours de laquelle des concepts et technologies clés ont été étudiées. Les modèles de logiciel mis au point au cours de la dernière phase ont fourni une simulation partielle de la couche physique de la technologie WiMAX mobile. Une excellente compréhension a été acquise sur la technologie WiMAX mobile et de ses limites dans un environnement simulé. Les simulations ont montré que la performance de la couche physique WiMAX est fortement dépendante du canal de propagation par lequel les signaux RF se propagent.

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Executive summary

Design and development of basic physical layer WiMAX network simulation models

Bob Szeker; DRDC Ottawa CR 2008-296; Defence R&D Canada – Ottawa; January 2009.

In order to support the Canadian Forces in the area of new and upcoming fourth generation (4G) wireless communications systems, the Defence Research and Development Canada - Ottawa (DRDC Ottawa) Modern Communications Electronic Warfare (MCEW) group started an Advanced Research Project (ARP) on emerging wireless systems. One particular 4G standard of interest is the latest IEEE 802.16e-2005 standard known as WiMAX. In order to support the research and development efforts to investigate this standard, the MCEW group started the development of computer simulation models of this new standard. The intent of these models is to understand the signaling environment of this standard to be ready to support present and future client needs in this emerging and quickly evolving technology.

The task of developing simulation models commenced with the modeling of a fixed WiMAX system physical layer per the original IEEE 802.16-2004 standard. This effort led to a good understanding of the key concepts and technologies employed by WiMAX. Several other simulation models were produced of increasing complexity. The final models produced were based on the IEEE 802.16e-2005 standard and simulated a mobile WiMAX physical layer. These computer models incorporated some of the advanced features inherent to mobile WiMAX systems. The simulation results gave an appreciation of how the performance of the WiMAX physical layer is dependent on the communications channel through which signals propagate. In order to maintain an adequate quality of service, the physical layer must rely heavily on special coding, multiplexing and modulation techniques to combat delay spread, inter-symbol interference and signal degradation due to random noise.

WiMAX technology is complex, as evidenced by the WiMAX standard which is over 900 pages long. The effort to develop computer simulation models began to the process of unraveling the complexities of this technology. A considerable amount of effort was exerted to become cognizant with WiMAX technology and to develop limited but accurate computer simulation models of the WiMAX physical layer. The lessons learned provide a solid foundation for future simulation work. Future plans call for expanding the current software simulation model to one of a complete WiMAX network cell. This simulation model will include a base station and multiple mobile stations, both operating on the uplink and downlink, and will use advanced concepts such as adaptive modulation and coding, multiple input and output antennas and others.

Sommaire

Design and development of basic physical layer WiMAX network simulation models

Bob Szeker ; DRDC Ottawa CR 2008-296 ; R & D pour la défense Canada – Ottawa ; janvier 2009.

Afin d'appuyer les Forces Canadiennes dans le domaine de la nouvelle et future quatrième génénation (4G) de systèmes de communications sans fil, le groupe Communications Modernes Guerre Électronique (CMGE) de Recherche et Développement pour la Défense Canada - Ottawa (RDDC Ottawa) a débuté un projet de recherche avancé sur les systèmes sans fil émergeants. Une norme 4G d'intérêt particulier est la toute dernière norme IEEE 802.16e-2005 mieux connue sous le nom de WiMAX. Afin d'appuyer les efforts de recherche et développement pour étudier cette norme, le groupe CMGE a débuté le développement de modèles de simulation par ordinateur pour ce nouveau standard. Le but de ces modèles est de comprendre l'environnement de signalisation de cette nouvelle norme pour être prêt à soutenir les besoins présents et futurs des clients sur cette technologie émergente qui évolue rapidement.

La tâche visant à développer les modèles de simulation a commencé avec la modélisation de la couche physique d'un système WiMAX fixe selon la norme IEEE 802.16-2004 d'origine. Cet effort a conduit à une bonne compréhension des concepts clés et des technologies employés par WiMAX. Plusieurs autres modèles de simulation ayant des niveaux croissants de complexité ont été produits. Les modèles finaux produits ont été basés sur la norme IEEE 802.16e-2005 et ont servi à simuler la couche physique de la technologie WiMAX mobile. Ces modèles informatisés ont intégré des fonctionnalités avancées inhérentes aux systèmes WiMAX mobiles. Les résultats de simulation ont donné une idée sur la façon dont la performance de la couche physique WiMAX est dépendante du canal de communication par lequel les signaux se propagent. Afin de maintenir une qualité de service satisfaisante, la couche physique doit s'appuyer fortement sur les techniques de codages spéciaux, de multiplexage et de modulation pour combattre l'étalement des retards dû à la propagation, les interférences entre les symboles et la dégradation du signal causée par le bruit aléatoire.

La technologie WiMAX est complexe, comme en témoigne la norme WiMAX qui est de plus de 900 pages. L'effort visant à développer des modèles de simulation par ordinateur a démarré le processus de déchiffrage des complexités de cette technologie. Une quantité considérable d'efforts a été effectuée pour devenir averti sur la technologie WiMAX et de mettre au point des modèles de simulation par ordinateur limités mais précis de la couche physique WiMAX. Les leçons tirées de l'expérience fournissent une base solide pour de futurs travaux de simulation. Les plans futurs appellent à l'expansion du modèle logiciel de simulation actuel à celui d'une cellule complète d'un réseau WiMAX. Ce modèle de simulation comprendra une station de base et plusieurs stations mobiles, les deux opérant à la fois sur la liaison directe et inverse, et fera appel à des concepts avancés, tels que la modulation et le codage adaptatifs, les antennes entrées multiples sorties multiples, et autres.

Table of contents

List of figures

List of tables

1 Introduction

This final progress report details the work performed in the design and development of a WiMAX network physical layer simulation model over the 6-month period from 14 April to 14 November, 2008. The work was performed under government contract number W7714-050965/001/TOR per Annex H of the Statement of Work.

The development of the simulation models was divided into 3 phases during which various software models and versions were developed. Interim progress reports were submitted to the Scientific Authority at the end of each milestone that included all software generated.

The first software version was developed during the period of 14 April to 30 May, 2008. The emphasis of the initial phase was more on research than development, as the fundamental principles of WiMAX needed to be investigated and studied. The first simulation version was therefore a simulation of the IEEE 802.16-2004 standard for a fixed WiMAX physical layer. [1]

The second software version was developed during the period of 1 June to 22 August, 2008. The software version developed during the 2nd phase focused on refinement of the various algorithms developed during the 1st phase and on further research and study. Several textbooks on WiMAX technology were studied in detail to assist with code development. A library of pertinent articles and white papers were collected from the World Wide Web.

The third software version was developed during the period of 22 August to 4 November, 2008. The software version developed during the 3rd and final phase was the first version to model a mobile WiMAX physical layer per the IEEE 802.16e-2005 standard. [2] This version models the downlink and includes advanced concepts such as scalable OFDMA and subchannel permutation modes.

The following sections describe and summarize all software versions produced under each development phase.

2 Background

The specifications for a fixed WiMAX network were originally published in the IEEE 802.16-2004 standard. Amendments to the original document, such as IEEE 802.16e-2005 for mobile applications were added later. The development of computer simulation models for fixed and mobile WiMAX physical (PHY) layers was a challenging task considering the scope and complexity of the WiMAX standard and its amendments.

The technologies inherent in WiMAX network have been employed by other communications standards such as WLAN, WiFi and other systems. These technologies consist of forward error correction (FEC) algorithms including randomization, convolutional coding and interleaving, orthogonal frequency division multiplexing (OFDM), various modulation types such as BPSK, QPSK, 16-QAM, and 64-QAM. Initially these concepts had to be researched and studied in detail. This initial familiarization was achieved through the use of textbooks and articles researched on the Web. The mathematics of some fundamental concepts such as Fourier transforms, convolutional coding techniques were also reviewed as a refresher. The references section at the end of this document contains a list of all documents used to assist code development.

The design and development of the WiMAX PHY layer was accomplished using the Mathworks 'Matlab' software. Matlab consists of a rich set of communications and signal processing functions that can be used readily for the simulation. The set of toolbox functions is too extensive to be described completely in this document; however all of the functions necessary for a complete implementation of the simulation model are available. For the WiMAX physical layer modeling, notable functions include fading channel models for Rayleigh and Rician channels with different Doppler spectra, convolutional coding and decoding (Reed-Solomon, Viterbi), and functions for signal mapping and modulation.

3 Simulation Versions

3.1 Version 1 - Basic Fixed WiMAX PHY Layer Simulation

3.1.1 Baseline

WiMAX is an emerging wireless broadband technology. Several companies have implemented computer simulation models of the WiMAX PHY layer; however the source code of such simulations is not readily distributed. In order to get the started quickly, existing code had to be found to serve as a take-off point or baseline. This first step was essential in order not having to develop a WiMAX simulation model from scratch. As the WiMAX standard is complex and extensive, developing a computer model from direct interpretation of the standard would have been too time consuming.

The first step taken was to investigate whether any existing WiMAX PHY layer simulations existed on the Mathworks Matlab users' website. A simulation model was found, entitled *Estudio y Simulación de la capa física de la norma 802.16 (Sistema WiMAX)* developed by Carlos Battlés Ferrer in June 2007. Although the program was coded in Matlab, unfortunately all program comments and variable names were in Spanish and were impossible to comprehend.

The text in the source files was translated from Spanish to English and variable names were replaced with their English equivalents. This made the source code legible and allowed it to be used as example code. More importantly, all of the program functions could be directly correlated to the specifications of the WiMAX standard.

The original and baseline version files are listed in Table 1.

The results of Ferrer WiMAX PHY layer simulation are output plots of the bit error rate (BER) versus the Eb/N0 (bit energy to noise power spectral density ratio). Several different scenarios can be simulated in which parameters for modulation types, communications channel types, encoding, nominal bandwidth, and cyclic prefix length can be varied. The Ferrer simulation does not allow multiple users and is for a fixed WiMAX network. The program allows the number of OFDM symbols transmitted to be specified by the user. The BER converges to a more accurate value as the number of symbols transmitted increases. The program simulates only the downlink; the transmission interface from the base station to the subscriber station.

The Ferrer simulation was adopted as the baseline for further code development as it served as a good take-off point for further understanding and interpretation of the WiMAX standard.

File number	Ferrer version (Spanish)	Simulation baseline version
1	aleatorio	randomize
2	BERteorica	BERtheoretical
3	bin_coef	bin_coef
4	bit_simbolo	bit_symbol
5	canalSUI	channelSUI
6	CIRpowers	CIRpowers
7	codificador	encoder
8	creacionsimbolo	createsymbol
9	cyclic	cyclic
10	decodificador	decoder
11	dibujar	draw
12	estimacioncanal	estimatechannel
13	extraer_datos	extract_data
14	find_index	find_index
15	generapiloto	genpilots
16	generodatos	gendata
17	genh	genh
18	gray2bi	gray2bi
19	graytable	graytable
20	interleaving	inteleaving
21	mapear	map
22	parametros_constelacion	constallation_parameters
23	parametros_SUI	parameters_SUI
24	pb_pam_ray	pb_pam_ray
25	pb_psk_ray	pb_psk_ray
26	pb_qam_ray	pb_qam_ray
27	PruebaBW	BW_test
28	PuebaCanales	Channel_test
29	PruebaCodifico	Encode_test
30	PruebaGuarda	Guard_test
31	PruebaModula	Modulation_test
32	receptor	receiver
33	ReedSalomon	ReedSolomon
34	ruido	noise
35	sistema	system_simulation
36	substrleft	substrleft
37	transmisor	transmitter
38	viterbi	viterbi
39	wimax	wimax

Table 1: *Source and baseline version file names.*

3.1.2 Technical description

3.1.2.1 Fading channels

The simulation of the WiMAX PHY layer begins with modeling of the communications channel through which signals propagate from the transmitter to the receiver. Proper channel modeling is a critical part of the simulation as the signals experience attenuation, delay spread, Doppler frequency shifts (in case of a moving receiver), and multipath reflections that degrade the signal's quality as it passes through the channel. The signal propagation can be via line-of-sight and non-line-of-sight paths.

The model uses the SUI (Stanford University Interim) channel models to describe the fading channels for various urban and rural environments and terrain types. Six SUI channel models have been adopted that adequately describe various parameters that define a communications channel. These parameters include path loss, multipath delay spread, fading characteristics, Doppler spread and co-channel interference. [3]

Upon review and examination of the Ferrer model, it was concluded that the channel modeling was not correctly implemented. The Doppler spectrum for the SUI channel models was being set up as a classical Jakes model, which the SUI channels are not. Code changes were made to *channelSUI.m* as follows:

```
% Obtain the SUI channel parameters.
(powers, K, delay, Dop, ant_corr, Fnorm) = parameters_SUI(N_SUI);
% Convert path delays to microseconds.
tau = delays*1e-6;
% Calculate the frequency-selective fading channel object
% with a rounded Doppler spectrum.
h=ricianchannel(1/Fs, max(Dop), K, tau, powers);
h.DopplerSpectrum=doppler.rounded;
channel = h.PathGains;
```

The 'channel' quantity obtained above is a complex vector describing the discrete path gains. The variable '1/Fs' is the sampling period and is a function of the bandwidth and a sampling correction factor 'n' specified by the WiMAX standard.

3.1.2.2 OFDM symbol creation

The WiMAX PHY layer uses OFDM to combat multipath effects such as channel fades, intersymbol interference and delay spread through the use of orthogonal subcarrier frequencies. OFDM is a key component of WiMAX and is a combination of modulation and multiplexing. How an OFDM symbol is created is essential to the understanding of WiMAX.

The fixed WiMAX standard specifies that the available bandwidth is divided into 256 subcarrier frequencies. A total of 64 subcarrier frequencies are reserved for guard bands,

pilot frequencies and a DC component, leaving the remaining 192 subcarriers for data transmission. The transmitted data is multiplexed and modulated onto the 192 orthogonal subcarriers. The orthogonal nature of the subcarriers assures that these frequencies do not produce intermodulation products.

The first step of the OFDM symbol creation begins with determining how many bits need to be generated. This function is implemented in the *gendata.m* file. For each modulation type and coding rate combination, the WiMAX standard specifies the uncoded block size (UBS) required to form the OFDM symbol, however the UBS is easily calculated as follows:

For example, if the modulation type is 16-QAM, 4-bits are used to code each bit of the data. If the coding rate is $\frac{1}{2}$, then the UBS is: 192*4/2 = 384-bits or 48-bytes. Actually the UBS is 1-byte less as a zero-pad byte is added in a following Reed-Solomon encoder step. A Matlab random number generator (randint) is used to generate the initial random data bytes of simulated data.

The random data bytes generated by *gendata.m* are output as a [376 x 1] vector that enter the randomization stage of the forward error correction (FEC) chain. Data randomization introduces protection through information theoretical uncertainty by avoiding possible long, repetitive sequences of 1s and 0s, which otherwise may cause discrete tones in the modulated signal. The output of the randomizer function is also a [376 x 1] vector.

The randomizer stage is followed by the Reed-Solomon encoder which is implemented using the *ReedSolomon.m* function. For 16-QAM modulation and $\frac{1}{2}$ coding rate the WiMAX standard specifies [64, 48] Reed-Solomon encoding. Therefore 47-bytes (376-bits) enters the Reed-Solomon encoder, a zero-pad byte is added and the output is 64-bytes (512-bits). The output of the Reed-Solomon encoder is therefore a [512 x 1] vector.

Next, the Reed-Solomon encoded data enters a convolutional encoder of native rate $\frac{1}{2}$. The output vector is [1024 x 1]. This vector gets punctured for a rate of 4/3 as specified by the WiMAX standard. The overall convolutional coding rate is therefore $\frac{1}{2} * 4/3 = 2/3$. The output after puncturing is 128-bytes (1024-bits) / 4/3 = 96-bytes (768-bits). The overall coding rate for 16-QAM modulation example is therefore 48/96 = 2/3 as specified by the WiMAX standard. Figure 1 shows the forward error correction stages in the OFDM symbol creation process.

Next, the convolutionally encoded and punctured data enters a two-step interleaver to ensure that adjacent coded bits are mapped onto nonadjacent subcarriers. This procedure is performed by the *interleaving.m* function. The output of the interleaver is a [768 x 1] vector.

So far the data has been massaged through forward error correction (FEC) algorithms to guard it against inter-symbol interference. In the next step the data is modulated onto the subcarriers. This is accomplished by Gray encoding the data onto the constellation map of the modulation type used. In the simulation this is accomplished by the *map.m* function. The WiMAX standard specifies the constellation maps for BPSK, QPSK, 16-QAM and 64-

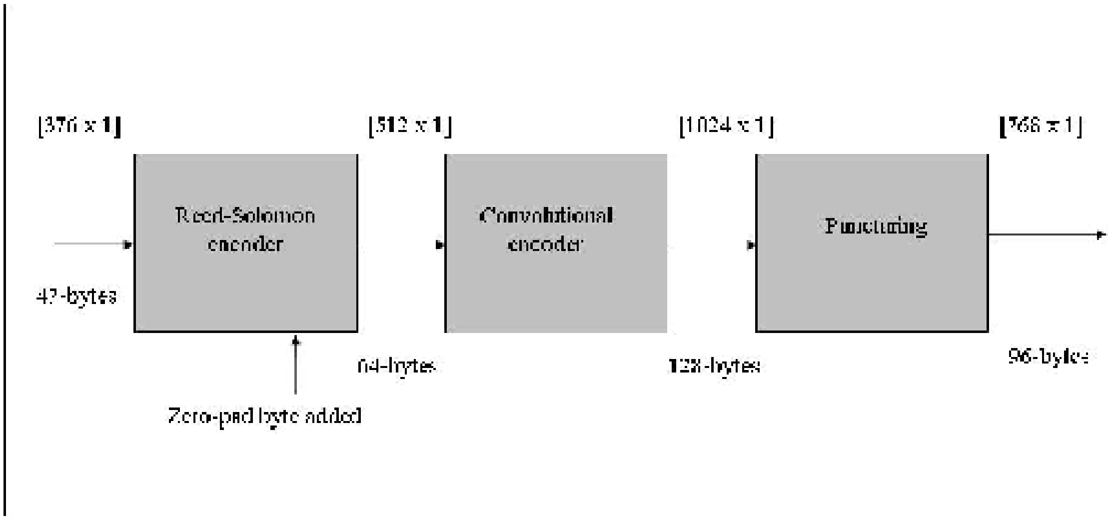

Figure 1: *The forward error correction chain block diagram*

QAM modulation types. For each constellation the standard also specifies a normalization factor 'c' to achieve equal average power.

Two changes were implemented to the *map.m* function and its sub functions of the original Ferrer simulation model. The *bit_symbol.m* function is called by *map.m* to calculate the symbol alphabet. The alphabet calculated did not conform to the WiMAX standard. Changes were made so that the symbol alphabet is calculated correctly. Also, in the current Matlab version 7.5.0.342 (R2007b) the 'genqammmod' function is obsolete. The following line of code:

```
v_encode = genqammod(v_data_decimal, constellation_gray);
```

was replaced with:

```
v_encode = modulate(modem.genqammod('Constellation',constellation_gray),
           v_data_decimal);
```

where 'v_encode' is the complex envelope of the message signal. This quantity is multiplied by the factor 'c' as mentioned above to normalize the average power. The output of the *map.m* function is a [1 x 192] complex vector.

The next step in OFDM symbol generation is the insertion of the 8 pilots onto the carrier locations specified by the WiMAX standard. This is performed by the *genpilots.m* function. The pilots are generated by a PRBS generator and are BPSK modulated. The output of *genpilots.m* is a [1 x 8] vector. The *genpilots.m* function was also modified as the BPSK modulation was not calculated correctly. The following lines of code:

```
A = 1 - wk;
```

B = 1 - (wk);
value_carrier = [A B A B B B A A];
mapped_pilots = 2*map(value_carrier, 1, Tx);

was changed to:

A = 1 - 2*wk;
B = 1 - 2*(wk);
value_carrier = [A B A B B B A A];
mapped_pilots = complex(value_carrier);

The mapped data and pilot vectors are passed to the *transmitter.m* function which completes the OFDM symbol by inserting the data, pilots, guard bands and DC components into their respective locations as specified by the standard. This is accomplished using the *createsymbol.m* function.

Once the OFDM symbol is complete, the *transmitter.m* function transforms the symbol to the time domain by applying the Inverse Fast Fourier Transform (IFFT). The OFDM symbol vector is [1 x 256]. The spectrum of the OFDM symbol is shown in Figure 2.

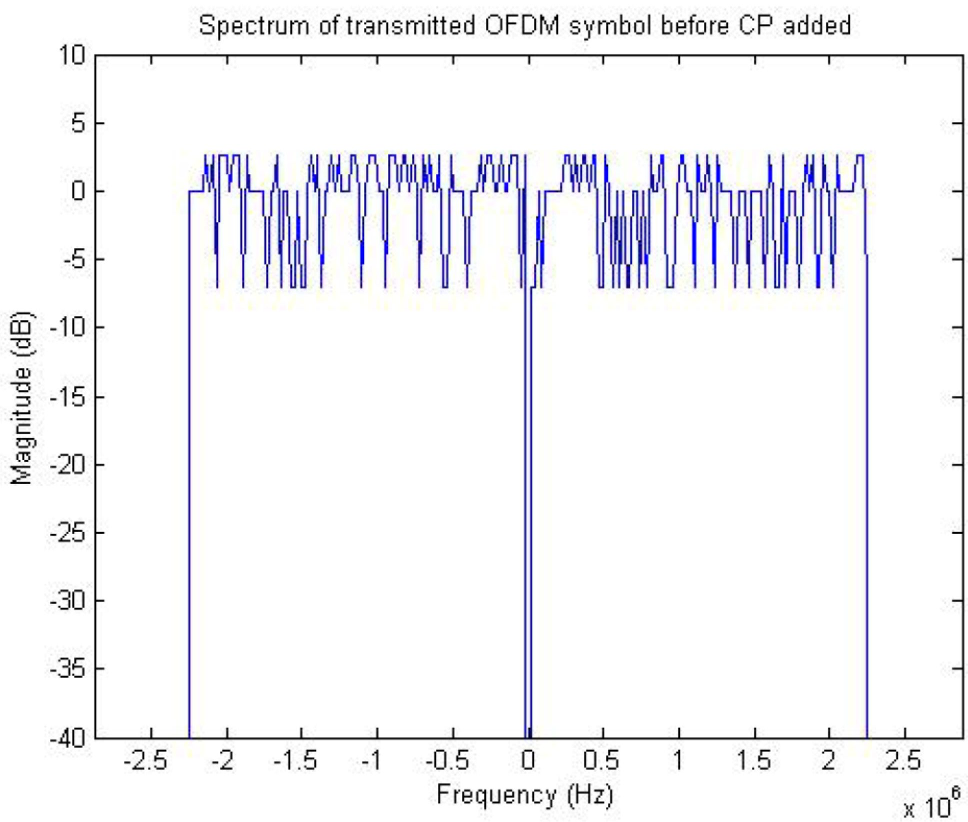

Figure 2: *Spectrum of OFDM symbol before CP added*

The cyclic prefix (CP) is inserted before the OFDM symbol is sent over the channel to combat delay spread and inter-symbol interference. The WiMAX standard specifies CP values of 1/4, 1/8, 1/16, and 1/32. This is done by the *cyclic.m* function. The last samples of the OFDM are copied to the beginning of the symbol.

The spectrum of the OFDM symbol after addition of the CP is shown in Figure 3. A CP length of $\frac{1}{4}$ is used in this example; therefore the output symbol length is $256 * \frac{1}{4} = 48 + 256 = 320$-bits or 40-bytes. It is interesting to note how the magnitude of the spectra fluctuates as compared to the underlying constant amplitude carriers. The OFDM symbol is very noise-like.

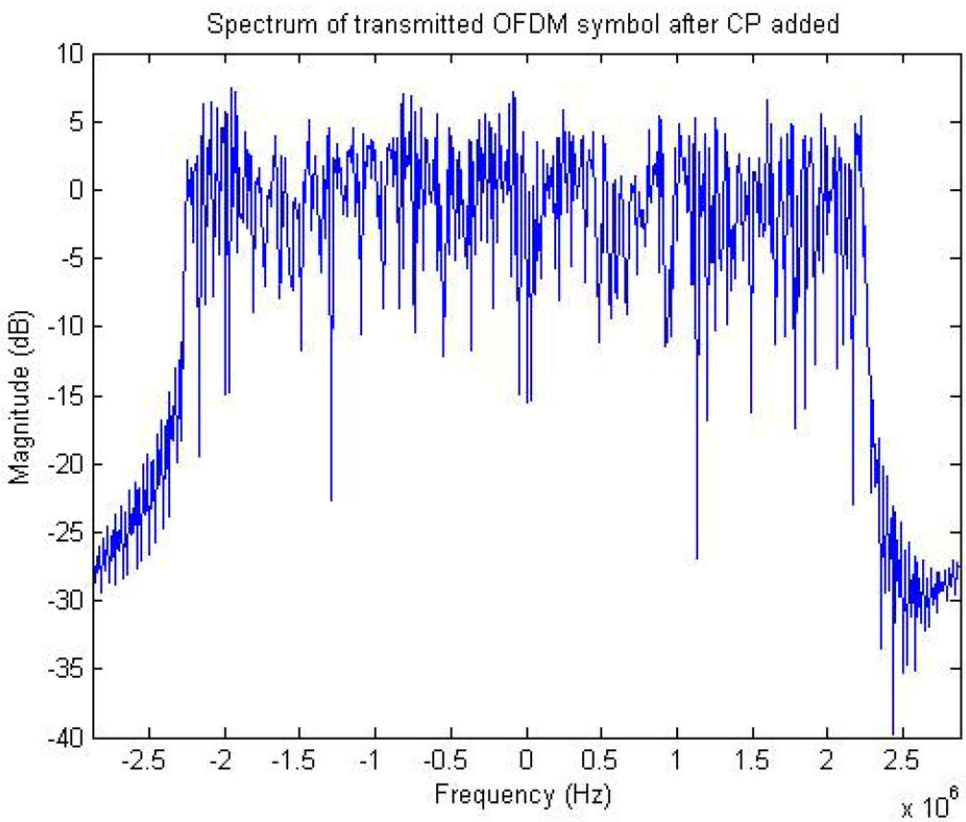

Figure 3: *Spectrum of OFDM symbol after CP added*

3.1.2.3 Channel simulation

In this step of the simulation, the completed OFDM symbol is transmitted over the communications channel. This step is modeled by the *system_simulaton.m* function. The *system_simulation.m* function uses the Matlab 'filter' command to simulate the propagation of the OFDM symbol over the fading channel. The spectrum of the received OFDM symbol is shown in Figure 4. The magnitude frequency response is plotted in red to show the channel effects on the received signal.

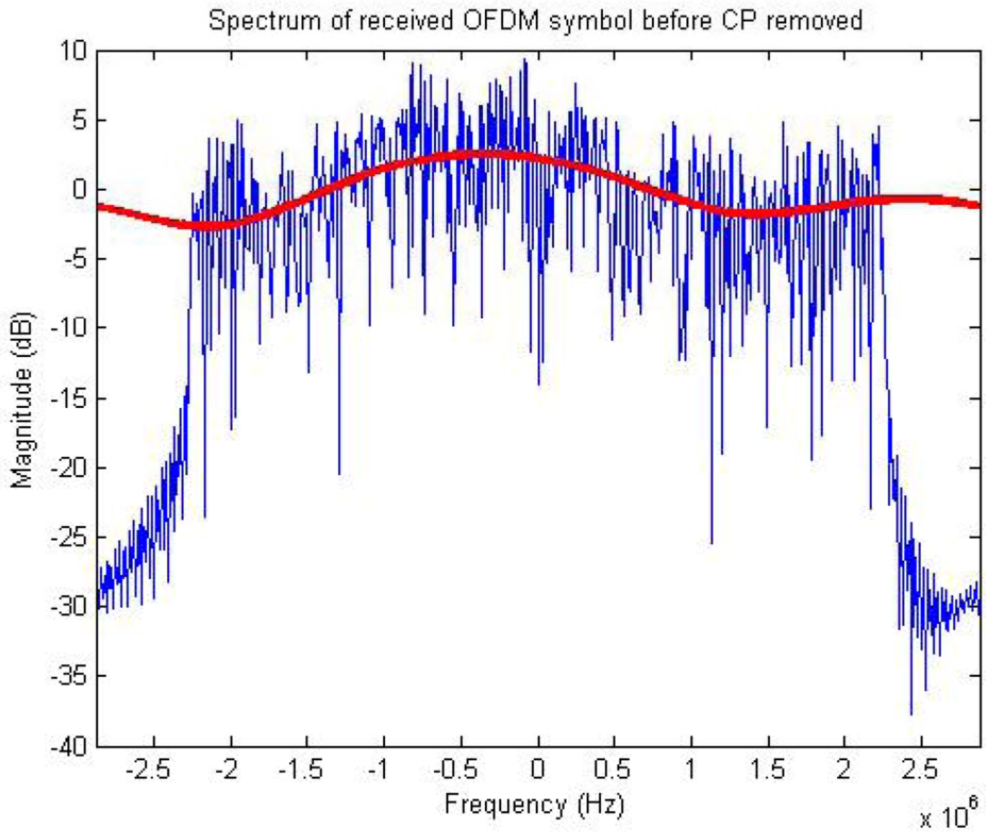

Figure 4: *Spectrum of received OFDM symbol before CP removed*

Immediately after the filtering stage of the simulation white Gaussian noise is added to the received OFDM symbol. This is done using the Matlab 'awgn' routine with various SNR values. Figure 5 shows the original signal constellation transmitted. Figure 6 shows the same constellation without noise added. Figure 7 shows the received signal constellation with SNR of 20-dB. The received signal constellations are the result of the fading channel characteristics and the effects of noise on the channel.

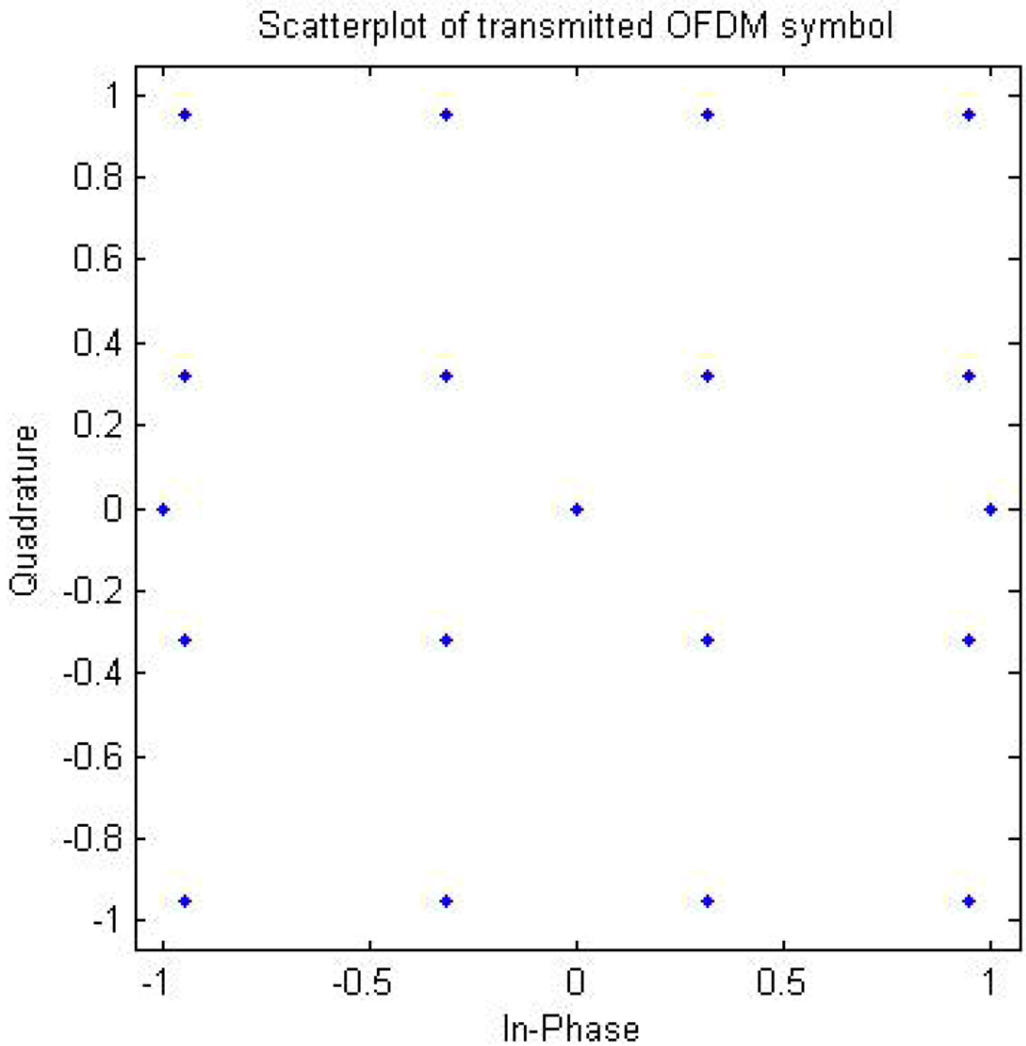

Figure 5: *Transmitted signal constellation*

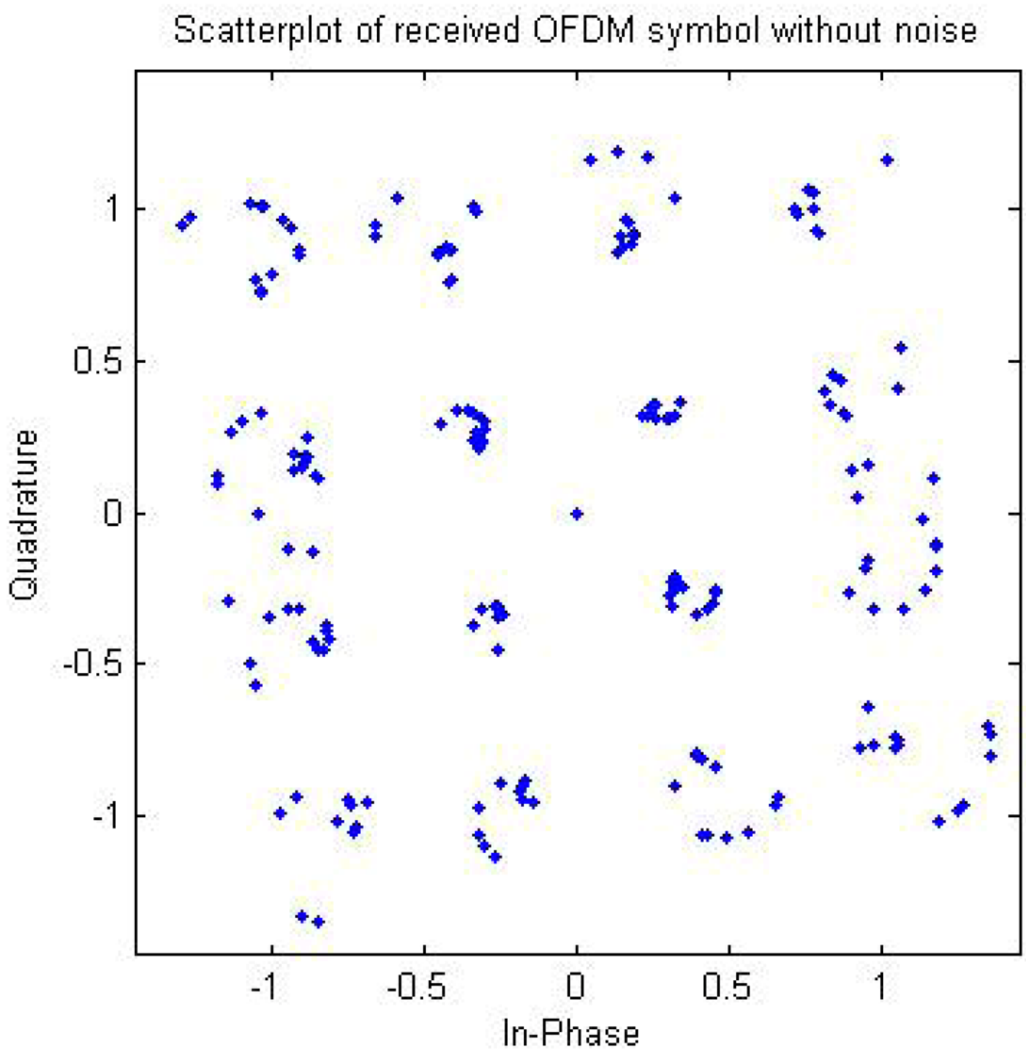

Figure 6: *Received signal constellation (no AWGN)*

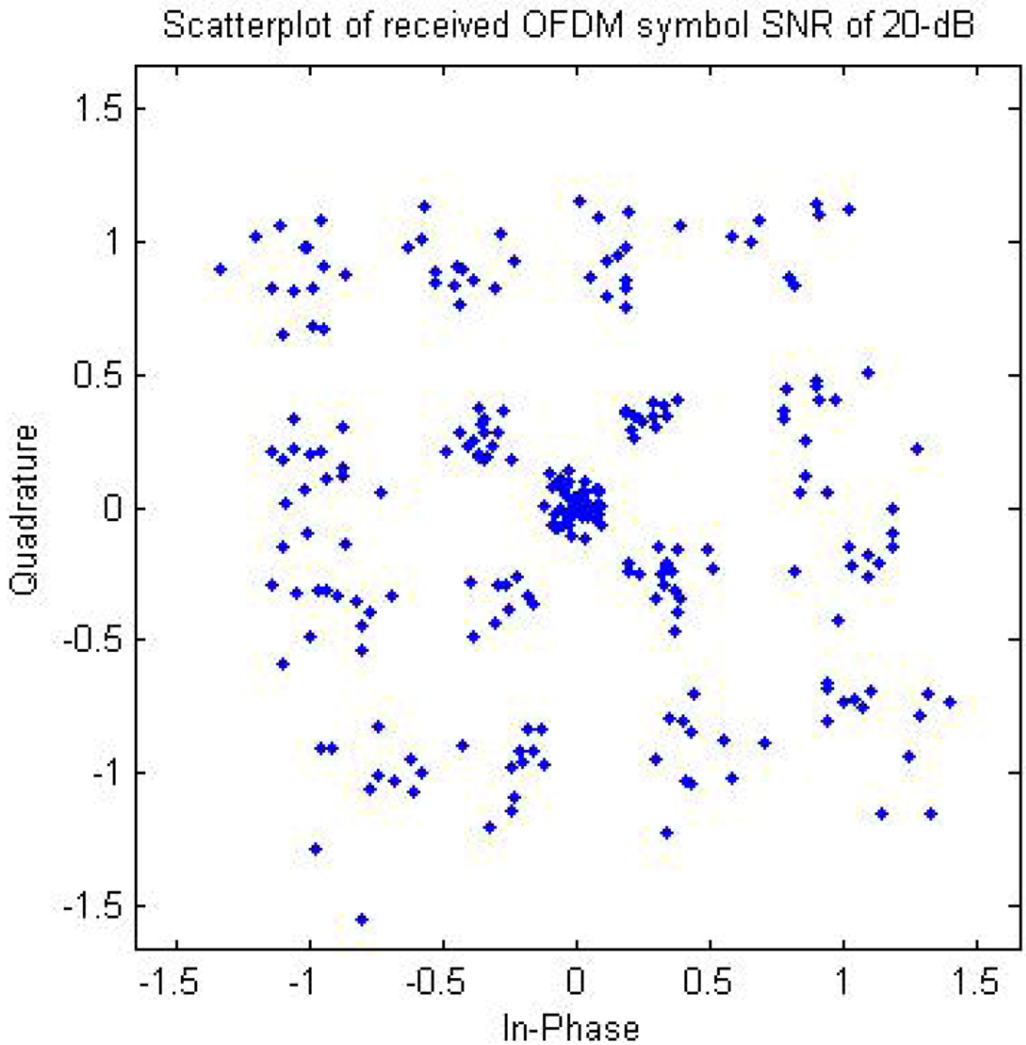

Figure 7: *Received signal constellation (AWGN 20-dB)*

The *receiver.m* function removes the CP and applies an FFT to transform the received signal into the frequency domain. When plotted, the spectra of the OFDM symbol with CP removed (Figure 8) are nearly identical to the original spectra of Figure 2 except for the fades introduced by the channel.

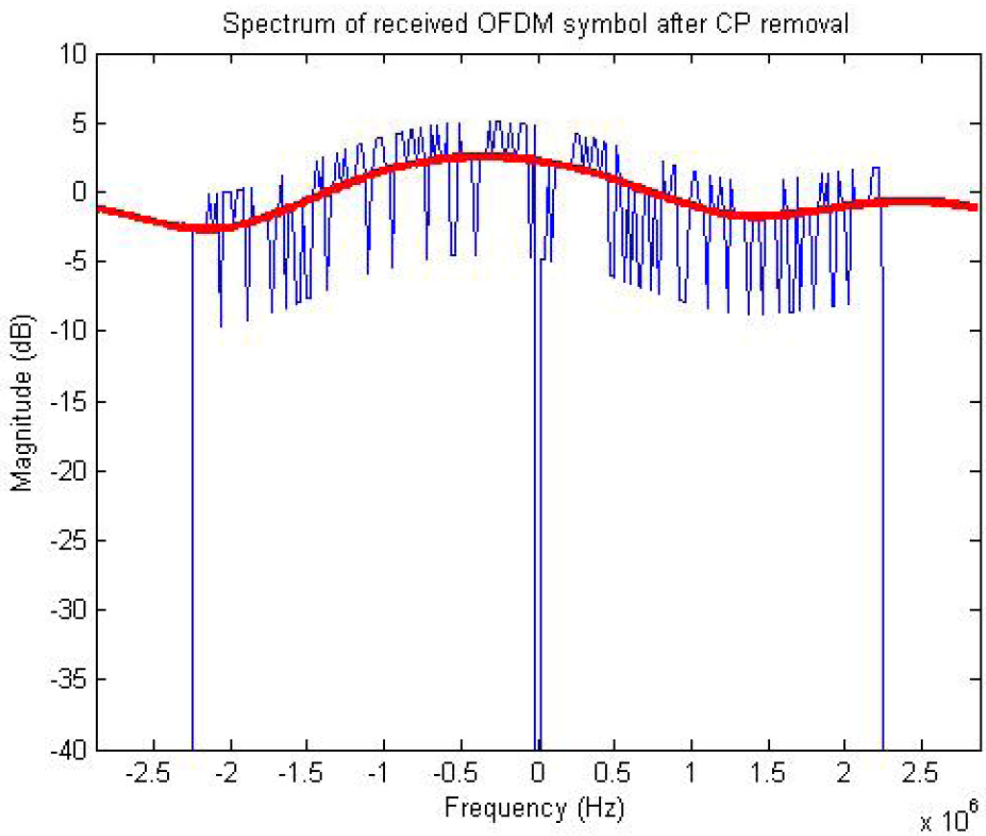

Figure 8: *Spectrum of received OFDM symbol after CP removed*

3.1.2.4 OFDM symbol decoding

The received signal vector is [1 x 320] which includes a CP of $\frac{1}{4}$. After the CP is removed the signal vector is [1 x 256]. The simulation's *decoder.m* function removes the pilots, guard bands and DC component using the *extract_data.m* function. In this version of the simulation the pilots are ignored after they are removed from the OFDM symbol and no channel estimation is done.

The signal is now a [1 x 192] vector which is decoded to recover the original signal. Decoding consists of applying the encoding steps is the reverse order, namely demodulating and de-interleaving the symbol, Viterbi decoding, Reed-Solomon decoding and de-randomization. These steps are not described here as they are basically the same steps described previously. The final decoded data vector is [1 x 376] and is the same size as the input data vector.

3.1.2.5 BER calculation

The bit error rate (BER) is calculated from the input and output vectors. This is done using the Matlab 'biterr' function which returns the number of bits that are different and the calculated ratio of bits that are in error to the total bits. The latter quantity is the BER which is plotted against the Eb/N0 value. This version of the simulation assumes that the BER and Eb/N0 values are one and the same, which they are not. These quantities are related by 'k' which is the number of bits per symbol and the coding rate. This discrepancy is addressed in subsequent simulation versions. Figure 9 shows a typical plot generated by the simulation.

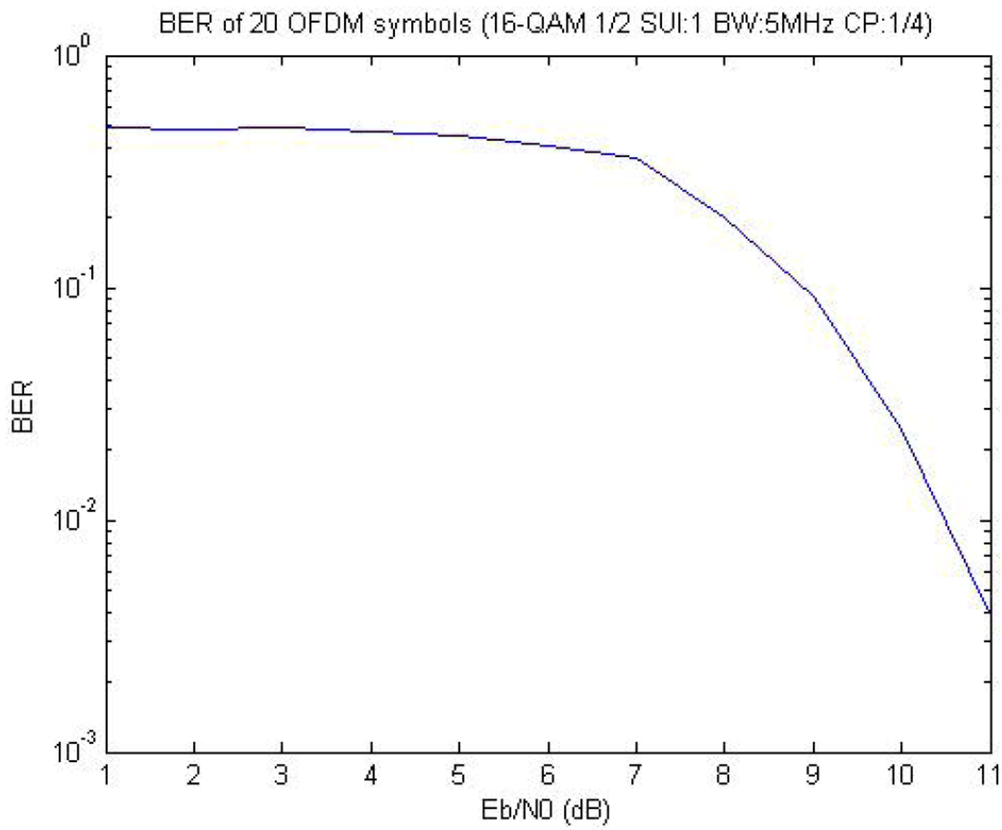

Figure 9: *Typical BER vs. Eb/N0 plot of 20 OFDM symbols transmitted*

3.1.3 Version 1 summary

The first simulation model version adopted an existing fixed WiMAX physical layer simulation as the baseline. This approach avoided having to develop source code from a direct interpretation of the WiMAX standard and saved valuable time. Several errors were discovered in the original source code and were corrected. Some new Matlab functions were incorporated. Use of the baseline code allowed for better and faster understanding of the

technologies used by WiMAX.

The work performed enabled a thorough review of the fundamental concepts used in a fixed WiMAX network. A good understanding of these concepts and methods was essential to progressing ahead with the design and implementation of more thorough fixed and mobile WiMAX physical layer simulations.

3.2 Version 3 - Improved Fixed WiMAX PHY Layer Simulation

3.2.1 Background

During the first phase of code development a baseline version (V1) of the simulation model was produced. This simulation model was limited to the modeling of a fixed WiMAX PHY layer per the original IEEE802.16-2004 standard. During the 2nd phase of development an extensive study was undertaken to extend the baseline version to include components defined for mobile WiMAX applications per the IEEE802.16e-2005 standard.

A mobile WiMAX system is based on scalable orthogonal frequency division multiple access (SOFDMA) and includes other advanced concepts such as subchannelization, channel estimation techniques, adaptive modulation and coding (AMC) and use of multiple transmit and receive antennas (MIMO). In order to understand these concepts, several textbooks were read and relevant articles were researched on the Web. Matlab programs were developed in order to implement these concepts into software.

During the 2nd phase the original version of the baseline software (V1) was simplified. The total number of source files was reduced from 39 to 23. Several redundant or unused source files were removed.

The Version 3 (V3) simulation software models an OFDM-based fixed WiMAX PHY layer. The user can enter simulation parameters such as the channel model, nominal bandwidth, modulation type, coding rate, cyclic prefix length and others. However instead of transmitting random data, the program simulates the transmission of an image across the physical layer. This approach gives much better qualitative results, as the received image can be easily compared to the original image. For a quantitative description of the simulation a graph of the calculated bit error rate (BER) versus the bit energy to noise power spectral density ratio (Eb/N0) is plotted. The Matlab source file names for Version 3 are as shown in Table 2:

File number	File name
1	bit_symbol
2	channelSUI
3	constellation_parameters
4	createsymbol
5	cyclic
6	decoder
7	encoder
8	estimatechannel
9	extract_data
10	find_index
11	gendata
12	genpilots
13	interleaving
14	map
15	parameters_SUI
16	randomize
17	receiver
18	ReedSolomon
19	run_rgswimax_sim
20	system_simulation
21	transmitter
22	validate_input
23	viterbi

Table 2: *Version 3 source file names.*

3.2.2 Program execution

The V3 simulation is executed by calling the *run_rgswimax_sim.m* file. The following dialog message appears:

```
===========================================================
=== Simulation program for downlink WiMAX PHY layer
=== Version 3.0
===
=== Author : RGS
=== DRDC, Ottawa, Ontario
=== Date : August 2008
===
===
===========================================================

Enter SUI channel: 1 to 6 (AWGN=0) [1]:
Enter modulation type: 1-BPSK, 2-QPSK, 3-16QAM, 4-64QAM [3]:
Enter 16QAM code rate: 2/3, 5/6 or 0 (no encoding) [2/3]:
Enter CP value: 1/4, 1/8, 1/16, 1/32 [1/4]:
Enter nominal BW (MHz): 20,10,5,3.5,1.25 [5]:

SNR range 10.00 dB to 16.00 dB will be simulated
Enter SNR steps (dB): 0.10 to 1.00 [0.50]:
Save input data to file? 0 or 1 [0]:
Simulation input data will not be saved..

Running simulation..
```

Default values are available for each input parameter and parameter checking is performed. The user can only specify values selected from the list shown for each parameter. For example, values of 1, 2, 3, or 4 can be entered for modulation type. Other values are not accepted and the user is prompted to re-specify a correct value.

The simulation transmits a JPG image with array dimensions of 360,000-bytes (300x400x3 array). When the default burst profile is used by the simulation, 47-bytes are used to form the OFDM symbol. The simulation time per OFDM symbol was measured to be 0.75-seconds average. This implies a total of 1.6-hours to transmit the entire image. The total simulation time for generating 13-images (e.g. for SNR values ranging from 10.0-dB to 16.0-dB, in 0.5-dB increments) is approximately 20.8-hours. The following figure shows the display while the simulation is executing.

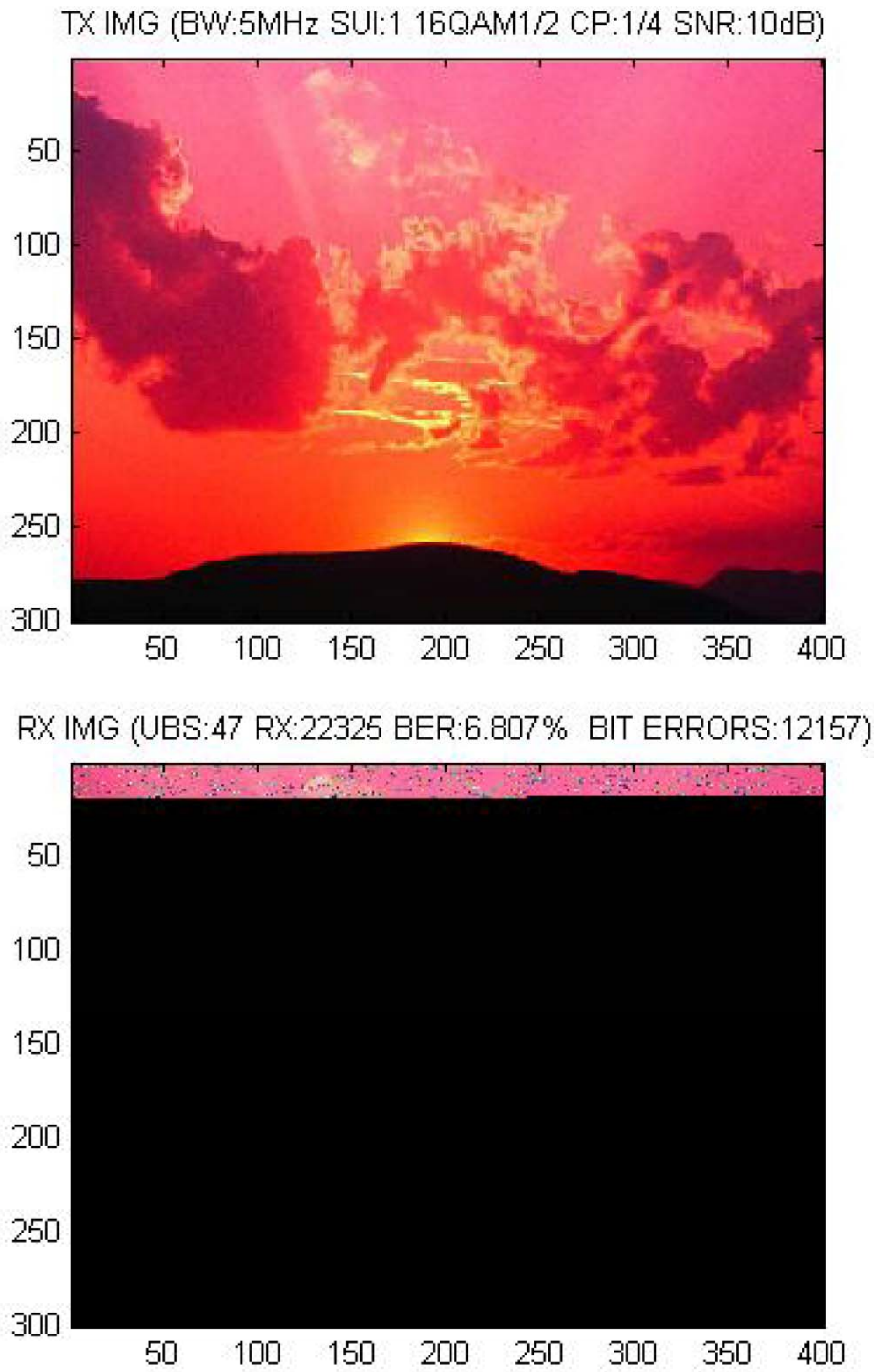

Figure 10: *Transmitted and received images*

The upper portion of Figure 10 shows the transmitted image. The burst profile is 16-QAM modulation with a coding rate $\frac{1}{2}$. The length of the cyclic prefix is $\frac{1}{4}$ and the SNR is 10-dB.

The lower portion of Figure 10 displays the received image. At the time when the image was captured, a total of 22325-bytes were received out of which 12157-bits were in error. The instantaneous total BER is therefore 6.81%. The figure also shows the uncoded block size (UBS), which in this case is 47-bytes.

3.2.3 Simulation model changes

The *estimatechannel.m* source file was changed to incorporate a pilot-based channel estimation algorithm. The first version (V1) of the simulation used the known fading channel gains to extract the data from the received signal. The algorithm was based on the article "*Error Probability Minimizing Pilots for OFDM with M-PSK Modulation over Rayleigh Fading Channels*" [4].

The simulation resets the channel object during each iteration, effectively changing the path gain values for each transmitted OFDM symbol. This represents a dynamically varying channel. The figures show sample plots of the actual (blue) and estimated (red) channel responses captured at various iterations. Plots were generated both with AWGN (Figure 11) and without AWGN (Figure 12) for comparison. The plots give a qualitative indication of the accuracy of the channel estimation algorithm. Note that the actual and estimated curves overlap perfectly when no AWG noise is introduced into the channel.

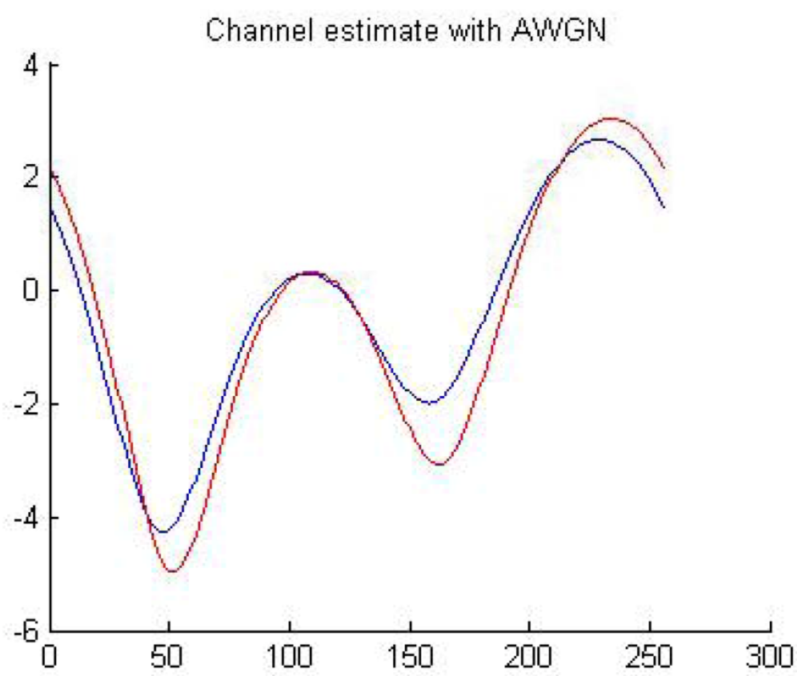

Figure 11: *Channel estimate with AWGN*

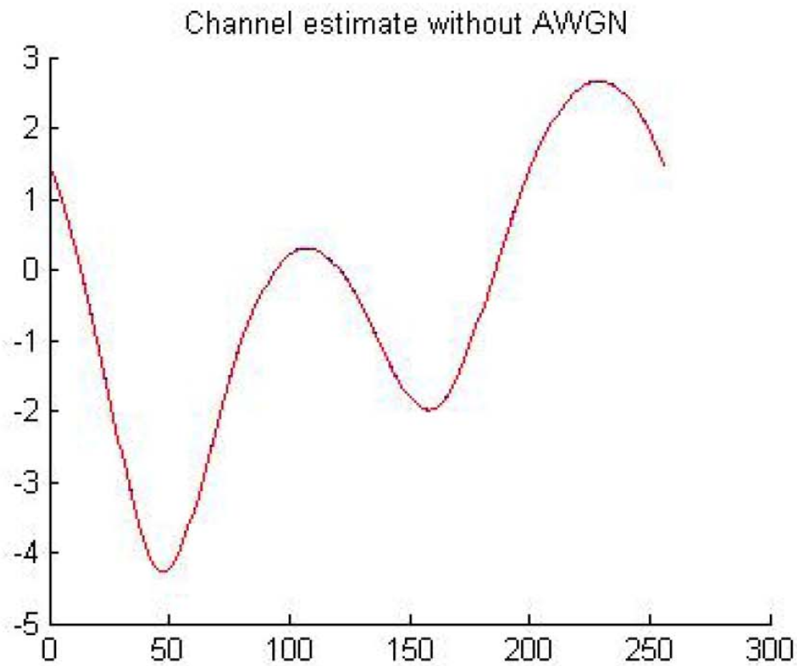

Figure 12: *Channel estimate without AWGN*

3.2.4 Simulation results

The figures shown in this section display the effects of the BER on the received image. The figures permit a qualitative understanding of the effects of the bit error rates that are acceptable or tolerable for image transmission across the WiMAX PHY layer. All images were created with 16-QAM modulation type, coding rate of $\frac{1}{2}$, cyclic prefix of $\frac{1}{4}$, and nominal bandwidth of 5.0-MHz. The SNR was increased progressively from 10.0-dB to observe the effects of the BER.

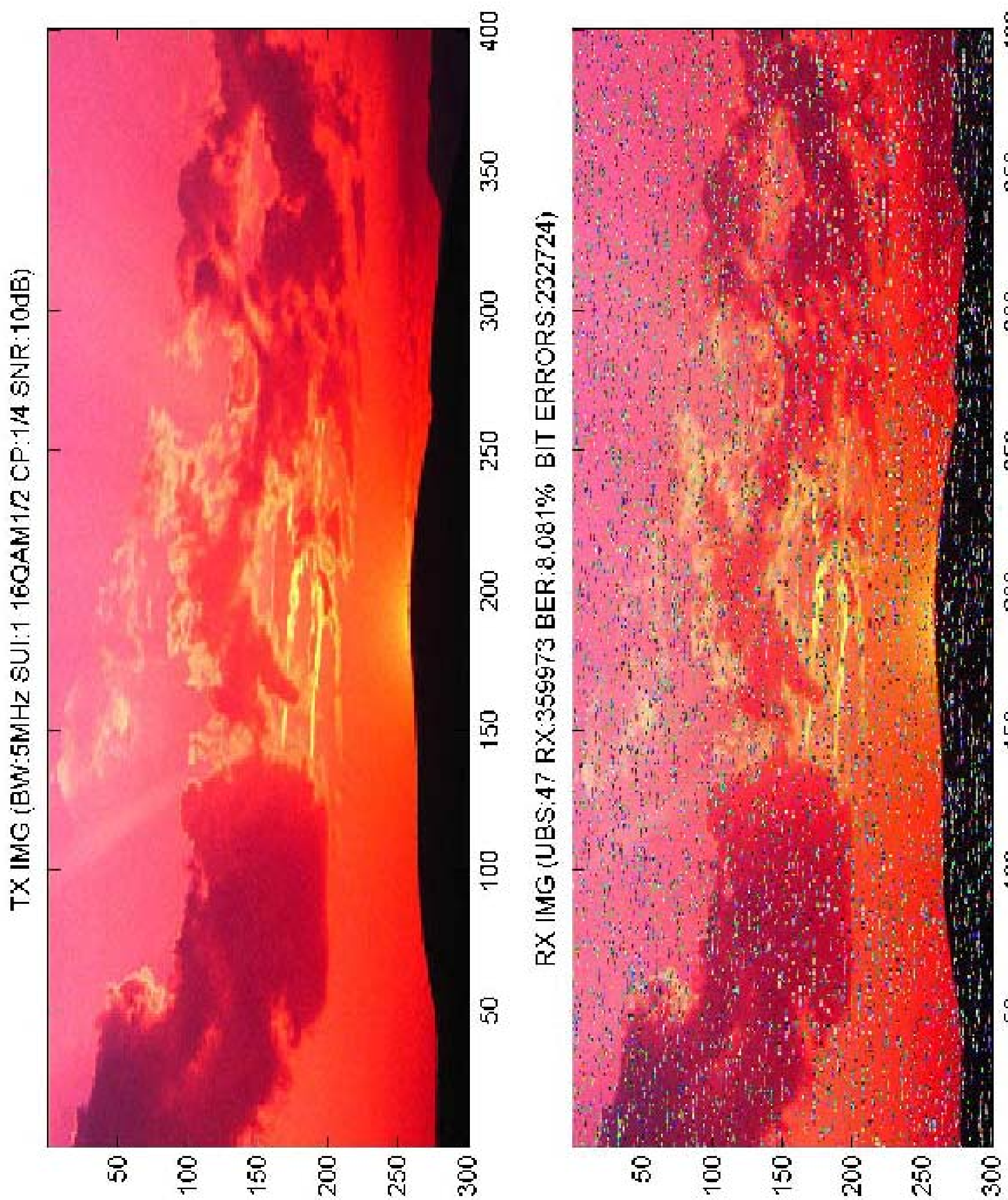

Figure 13: *Tx and Rx images, SNR 10-dB*

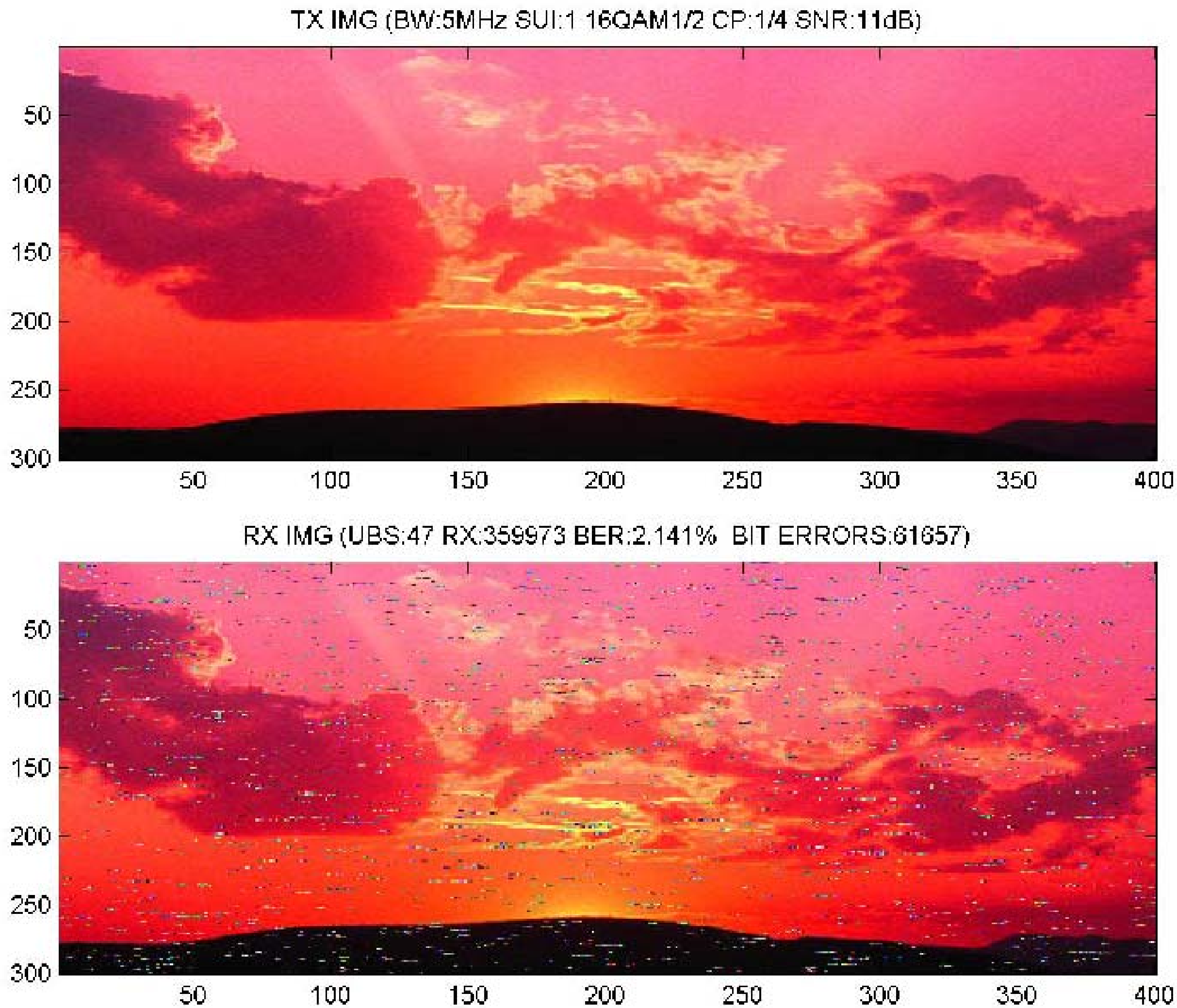

Figure 14: *Tx and Rx images, SNR 11-dB*

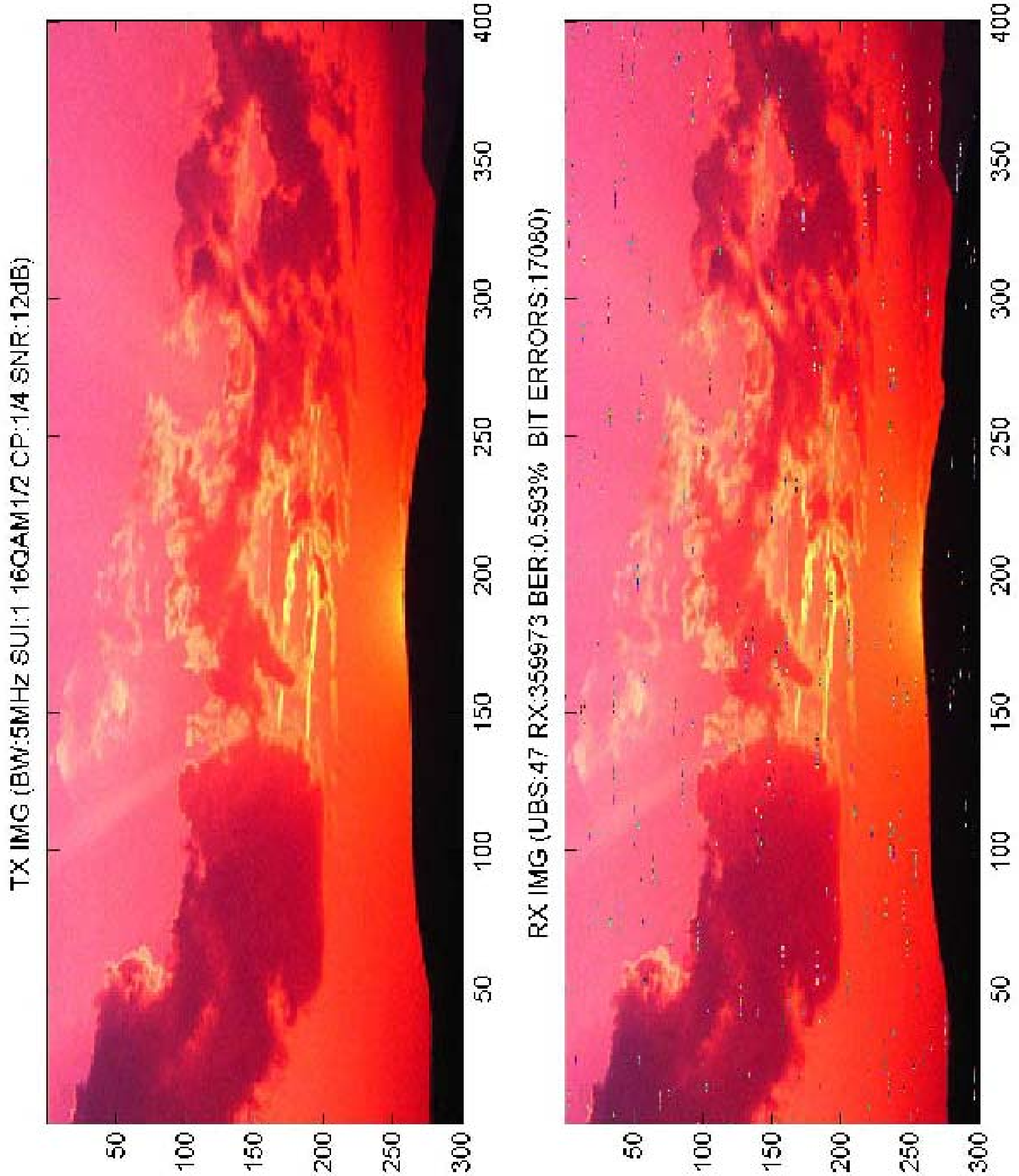

Figure 15: *Tx and Rx images, SNR 12-dB*

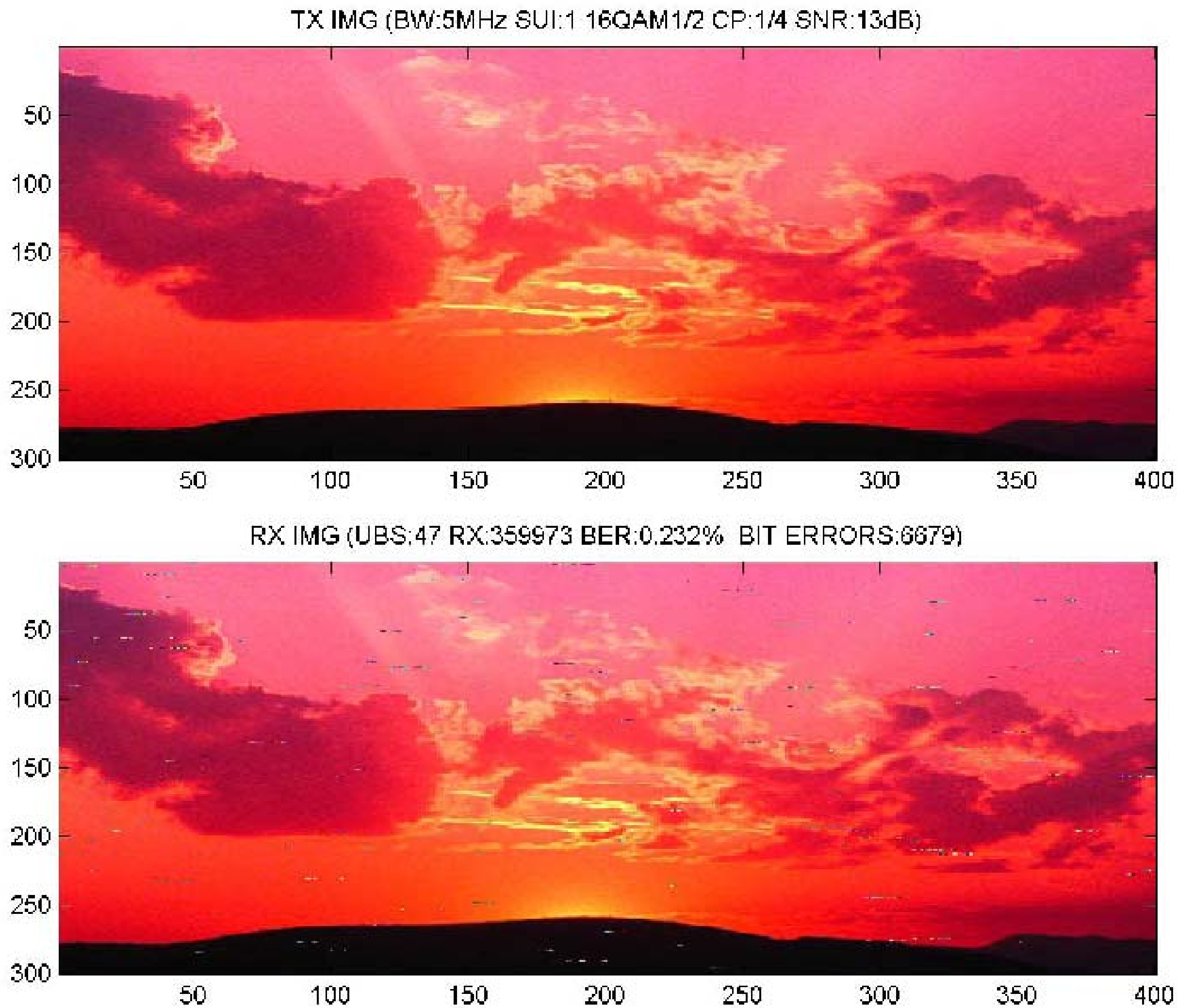

Figure 16: *Tx and Rx images, SNR 13-dB*

An acceptable minimum SNR value for image transmission is open to debate from the previous figures. In general the image quality increases as the SNR is increased for a given burst sequence. Figure 17 shows the graph generated by the simulation.

The BER is plotted against the Eb/N0 values, where Eb/N0 is related to SNR by the equation:

Eb/N0=SNR(dB) - 10*log10(k)

where k = coding rate * number of coded bits per carrier. For 16-QAM modulation, 4 coded bits are used per carrier.

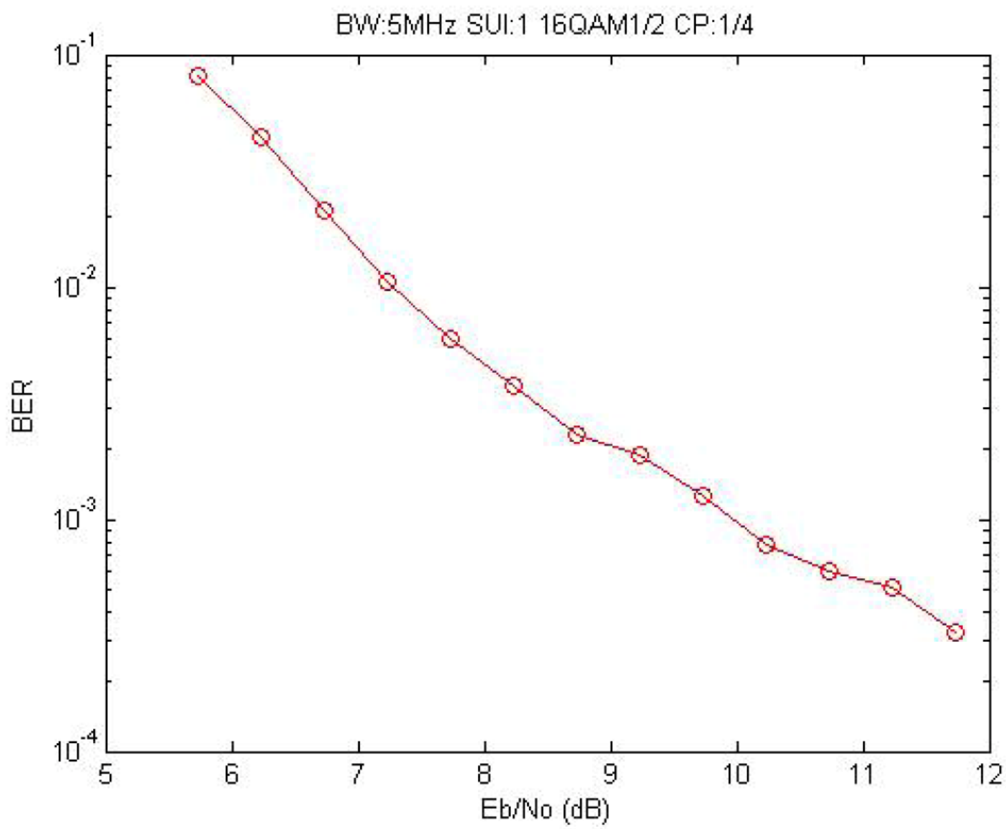

Figure 17: *Plot of BER vs. Eb/N0*

3.2.5 Version 3 summary

During the development of the Version 3 simulation model, the baseline code developed for the fixed WiMAX physical layer simulation was modified. Instead of transmitting random data patterns to generate the OFDM symbols, the simulation uses an existing (JPG) image. The transmitted image and the received image can be compared for a qualitative

understanding of the PHY layer effects. The program plots the accumulated results for a quantitative analysis.

A channel estimation algorithm was incorporated into the code that is quite accurate and is based on published work. The V3 simulation program uses the estimated fading channel gains to recover the received OFDM symbol.

During the 2nd phase of development, work was started to modify the simulation to include scalable OFDMA which is the basis of a mobile WiMAX PHY layer. Routines were coded to enable subchannelization; a fundamental feature of mobile WiMAX.

To summarize the work performed, the entire simulation was described in detail in a PowerPoint presentation entitled "*IEEE802.16-2004 WirelessMAN OFDM WiMAX DL PHY Layer Simulation*". This document serves several purposes. It summarizes the simulation, reinforces understanding of the concepts involved, and serves as a presentation and educational tool. Figure 18 shows the first page of this document.

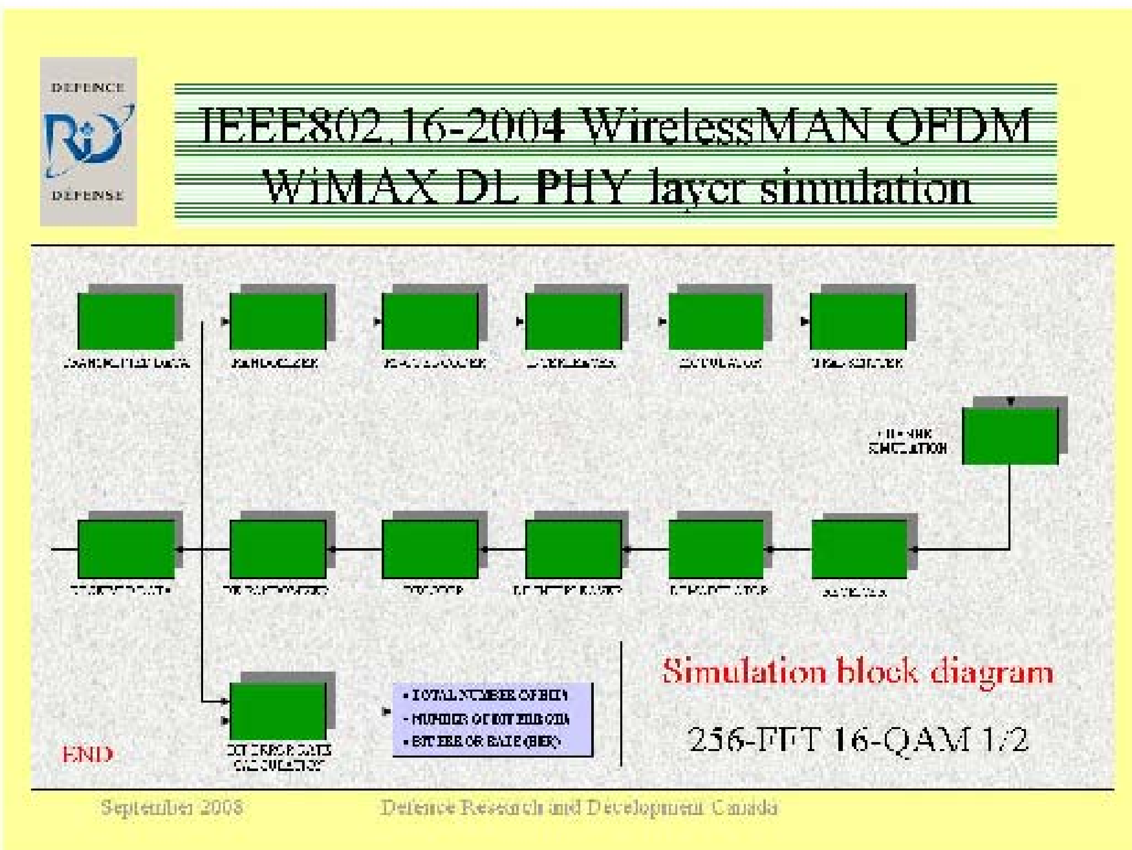

Figure 18: *Simulation block diagram*

3.3 Version 5 - Basic Mobile WiMAX PHY Layer Simulation

3.3.1 Background

During the 1st and 2nd phase of simulation development, important fundamental concepts were learned. These concepts were essential to develop an accurate, although limited, simulation model of a mobile WiMAX PHY layer as specified by the IEEE 802.16e-2005 standard.

Version 5 of the software models the downlink (DL) from the base station (BS) to a mobile station (MS). The model employs scalable OFDMA, subchannelization, and preamble-based channel estimation techniques. The software partially models the MAC layer as it generates pseudo-MAC layer management messages to the PHY layer. The simulation consists of the Matlab files shown in Table 3.

3.3.2 Technical description

A complete explanation of the mobile WiMAX PHY layer is beyond the scope of this document. Only brief explanations of key concepts are presented. The program flow is given in the following steps.

1. The model inputs several parameters such as the nominal bandwidth, the cyclic prefix, the SUI channel index, the signal-to-noise ratio, and other parameters required by the simulation. All input parameters use the 'ip_' prefix (i.e. ip_BW to specify the nominal input bandwidth).

2. The model selects the number of FFT points based on the nominal bandwidth specified. In mobile WiMAX the bandwidth can be 1.25, 5.0, 10.0 or 20.0 MHz corresponding to FFT points of 128, 512, 1024 and 2048 respectively. This implementation keeps the subcarrier spacing constant at 10.94-KHz. This technique is known as scalable OFDMA or SOFDMA. The nominal bandwidth is multiplied by a normalization factor specified by the standard.

3. The model generates Rician or Rayleigh fading channels to model the communications channel. As in previous simulation versions, 6 SUI channels can be specified to model various terrain types, scattering environments and Doppler frequencies.

4. The model defines 4 user IDs and 6 different downlink interval usage codes (DIUCs). A DIUC defines the modulation type, coding type and coding rate used for each DL burst or data region within a downlink subframe. Connection IDs (CIDs) are used to specify to the mobile station the DIUCs assigned to each user. The number of users, DIUCs and CIDs can be varied in the program.

The simulation uses the following input definitions:

ip_user_ID = [{'a10c'} {'b28f'} {'c30c'} {'d99f'}];
ip_DIUC = [0 1 2 3 4 5];

File number	File name
1	bit_symbol
2	constellation_parameters
3	cyclic
4	estimatechannel
5	find_index
6	find_preamble_128
7	find_preamble_512
8	find_preamble_1024
9	find_preamble_2048
10	form_preamble_128
11	form_preamble_512
12	form_preamble_1024
13	form_preamble_2048
14	gensubchan
15	gray2bi
16	interleaving
17	MAC_DL_MAP_msg
18	map
19	parameters_SUI
20	randomize
21	scpm_dl_fusc_128
22	scpm_dl_fusc_512
23	scpm_dl_fusc_1024
24	scpm_dl_fusc_2048
25	scpm_dl_pusc_128
26	scpm_dl_pusc_512
27	scpm_dl_pusc_1024
28	scpm_dl_pusc_2048
29	viterbi
30	wimax

Table 3: *Version 5 source file names.*

ip_CID = [{[1 2 3 4]} {[1 2]} {[3 4]} {[1]} {[2]} {[3]}];

Here CID 1 uses DIUC 0 and is assigned to users 1, 2, 3 and 4; therefore all users will receive the data sent on this connection. This is a form of multicast operation. CID 6 uses DIUC 5 but is intended only for user 3 with ID 0xc30c.

5. The above parameters are normally issued to the PHY layer by a MAC DL-MAP management message. The MAC layer message also informs the PHY layer on how the DL subframe is to be structured. It specifies the start and end symbols and subchannels within the subframe for each DIUC. The DL MAP message is transmitted to the MS in the DL subframe so the MS knows how to decode (unmap) the data.

The model calls the *MAC_DL_MAP_msg.m* function to generate a pseudo-MAC layer management message. The returned message is randomized, convolutionally encoded, interleaved and modulated. QPSK CC $\frac{1}{2}$ is used as specified by the standard. (The DL MAP, UL MAP and frame control header are always transmitted using QPSK modulation as specified by the standard).

6. The model sets up a mapping matrix whose size is determined by the total number of OFDMA symbols and subchannels used. The number of symbols is limited by the frame duration which is typically 5-msec. The number of subchannels used depends on the FFT size (itself being a function of the bandwidth used). The mapping matrix is filled with the DIUCs defined by the MAC DL MAP message.

7. The model generates 2-Kbytes of random data to be transmitted on each DL burst and calculates the maximum number of concatenated slots available for each data region. A slot is the basic data unit in OFDMA. For DL FUSC (full usage of subcarriers) permutation mode, a slot is 1-OFDMA symbol by 1-subchannel. For DL PUSC (partial usage of subcarriers) permutation mode, a slot is 2-OFDMA symbols by 1-subchannel. Based on the DIUC assigned to a data region, the model calculates the uncoded block size (UBS) that can be mapped into each data region. The UBS is used to 'cut' portions of the random data that will completely fill each data region.

8. The model randomizes, convolutionally encodes, interleaves and modulates each data burst per the DIUC assigned by the mapping matrix.

9. The DL subframe matrix is generated. The size of this matrix is the number of FFT points used by the number of OFDMA symbols. This matrix holds all data that is ready to be transmitted across the interface.

10. Next, the frame preamble is generated based on the number of FFT points used and on the Cell ID assigned to each segment. Three segments are used within each cell corresponding to three transmit antennas. The preamble is created from pseudo-noise (PN) sequences defined by the standard. The preamble is BPSK modulated for reliable recovery even in worst case SNR conditions and carriers are boosted by 9.0-dB.

11. The model generates the frame control header (FCH) based on the FFT size. The FCH contains information on subchannelization, repetition coding, coding type and the length of the DL MAP message. The FCH is encoded, interleaved and modulated using QPSK CC 1/2 rate. The FCH is not randomized. The FCH is then mapped to slots in the DL subframe matrix using the PUSC subcarrier permutation mode.

Examples of FUSC and PUSC subcarrier permutations are shown in Figure 19 and Figure 20 respectively. In these figures, subcarriers (blue) and pilots (red) are grouped together to form a subchannel. The permutation depends on the symbol number and the DL permutation base, therefore the location of data and pilot subcarriers varies for each OFDMA symbol. A given subchannel will always contain a different subcarrier permutation for each symbol.

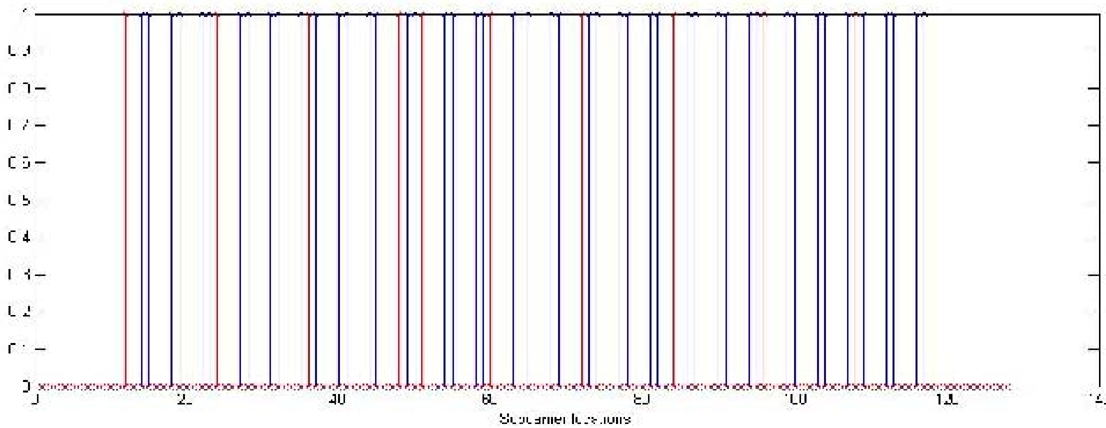

Figure 19: *Data and pilot subcarrier locations - DL FUSC 128-FFT subchannel 1*

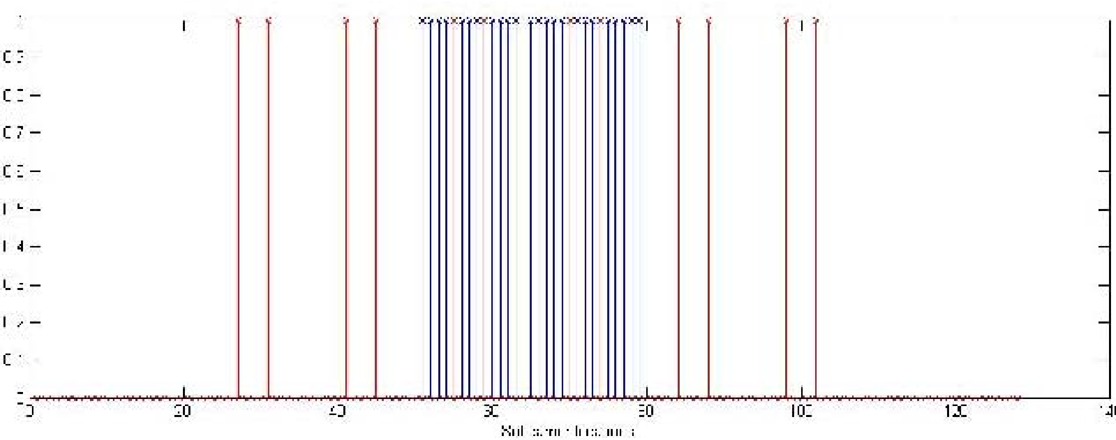

Figure 20: *Data and pilot subcarrier locations - DL PUSC 128-FFT subchannel 1*

12. The DL MAP is mapped to slots in the DL subframe matrix immediately after the FCH. DL MAP and FCH uses PUSC subcarrier permutation mode exclusively as specified by the standard. The region containing the FCH and DL MAP are called the 1st PUSC zone.

13. Finally the coded and modulated data is mapped to the DL subframe matrix as specified by the mapping matrix. The data is mapped using PUSC. A DL subframe may contain up to 8 zone switches. No zone switches are used to reduce simulation complexity.

14. The completed DL subframe matrix is now ready to be transmitted. The program transmits the subframe across the channel one OFDMA symbol at a time. The symbol is first transformed to the time domain using an inverse-FFT (IFFT) function and the cyclic prefix is then added to the signal. White Gaussian noise is added with level specified by the SNR. On the receiver (MS) side, the CP is first removed and the signal is transformed back to the frequency domain using the FFT function. All received signals are buffered.

15. The receive buffer contains all received signals, the first few samples of which are shown in Figure 21.

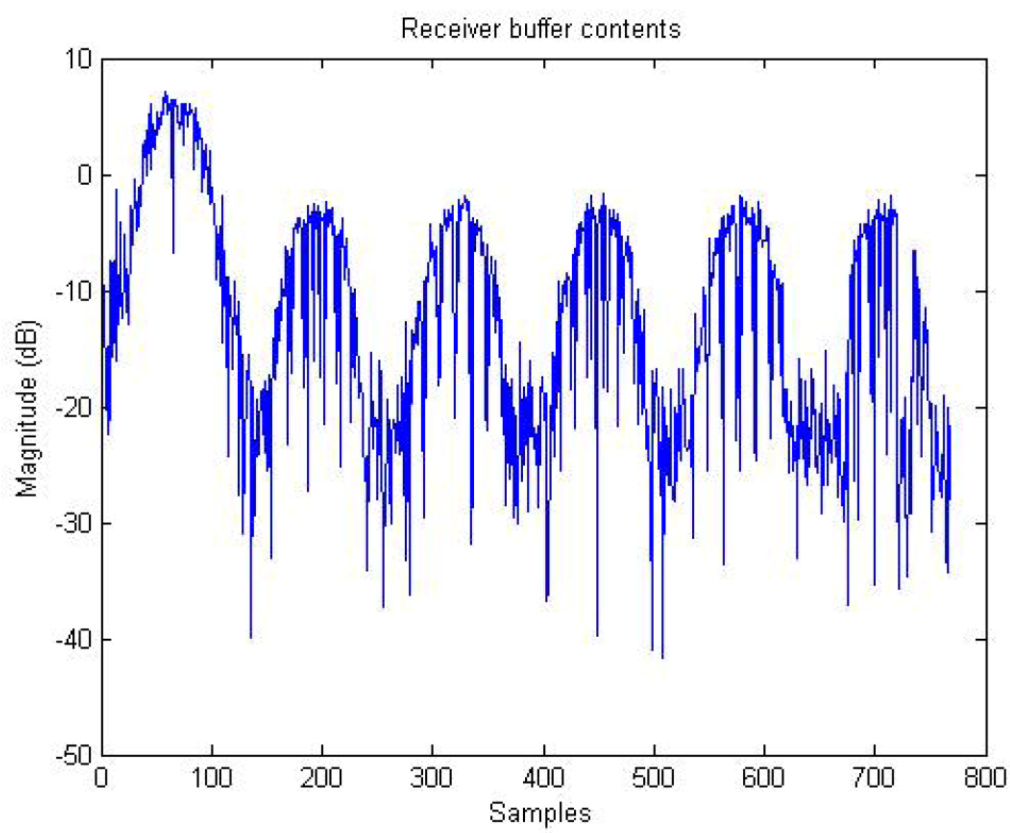

Figure 21: *Receive buffer contents*

Figure 21 shows the captured OFDMA symbols. The first symbol is the preamble which is boosted by 9.0-dB at the transmitter and marks the beginning of the DL subframe. The location of the preamble symbol can vary within the buffer. To reduce simulation complexity the preamble is conveniently located at the buffer's start.

The FFT size used can be readily determined by the receiver by counting the number of carriers that are above a given threshold. In the software model the detection threshold is variable and is set to 5.0-dB by default.

16. Once the FFT size used has been determined from the preamble, the simulation performs preamble-based channel estimation. Channel estimation is via the *estimatechannel.m* function. The estimate agrees quite well with the actual fading channel response as shown in Figure 22. Differences between the actual (blue) and estimated (red) curves are due to the AWGN noise introduced by the channel. The channel estimate improves with increasing SNR.

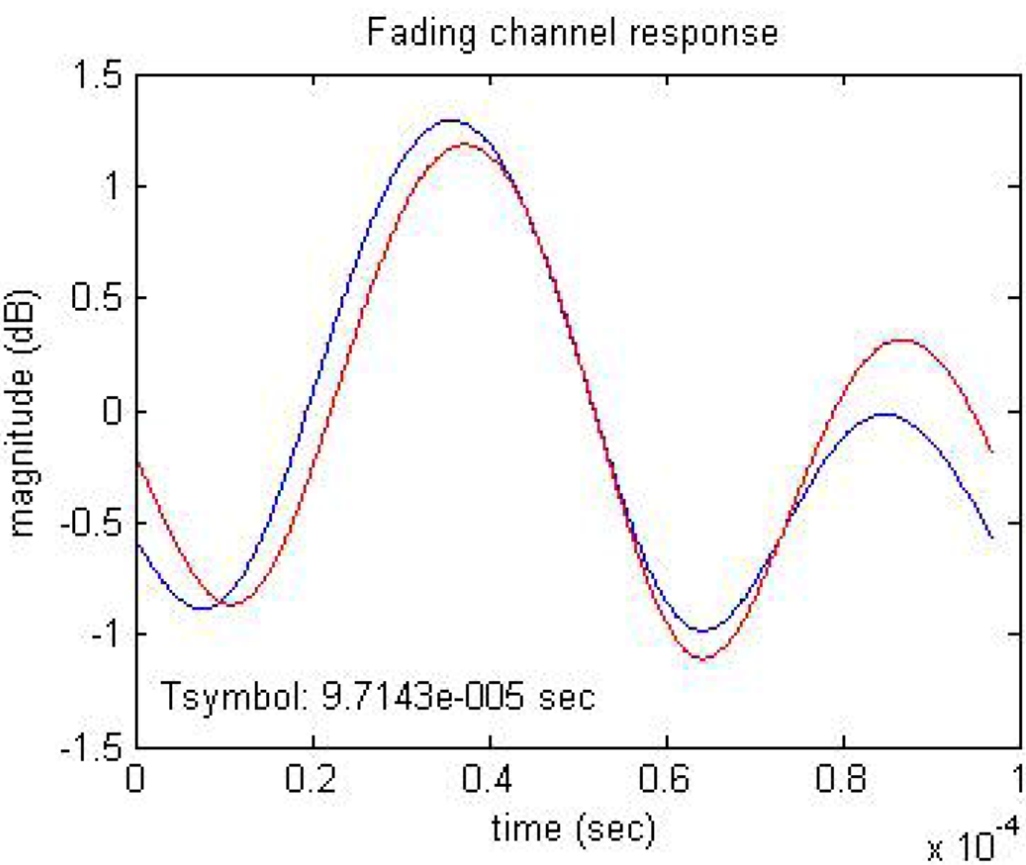

Figure 22: *Typical fading channel magnitude response*

17. The channel estimate is used to 'estimate' the transmitted symbol from the received symbol, as deep signal fades and peaks are eliminated. It is assumed that the channel does not vary considerably during the DL frame transmit time therefore all signals propagating

through the channel experience the same fades. The channel estimate is applied to the preamble as shown in Figure 23 and Figure 24. The actual channel response is overlaid in red. The mean value of the estimated preamble is 9.0-dB.

18. The simulation extracts the Cell IDs from the estimated preamble. The PN sequences obtained are compared to tables of known sequences defined by the standard. In this manner the Cell IDs on each segment are obtained and compared to their known, transmitted values.

19. Finally the program extracts the OFDMA symbols following the preamble, applies the channel estimate and decodes the frame control header (FCH). The FCH is mapped differently in the DL subframe depending on the FFT size used. The unmapped and decoded FCH is compared against the known transmitted values.

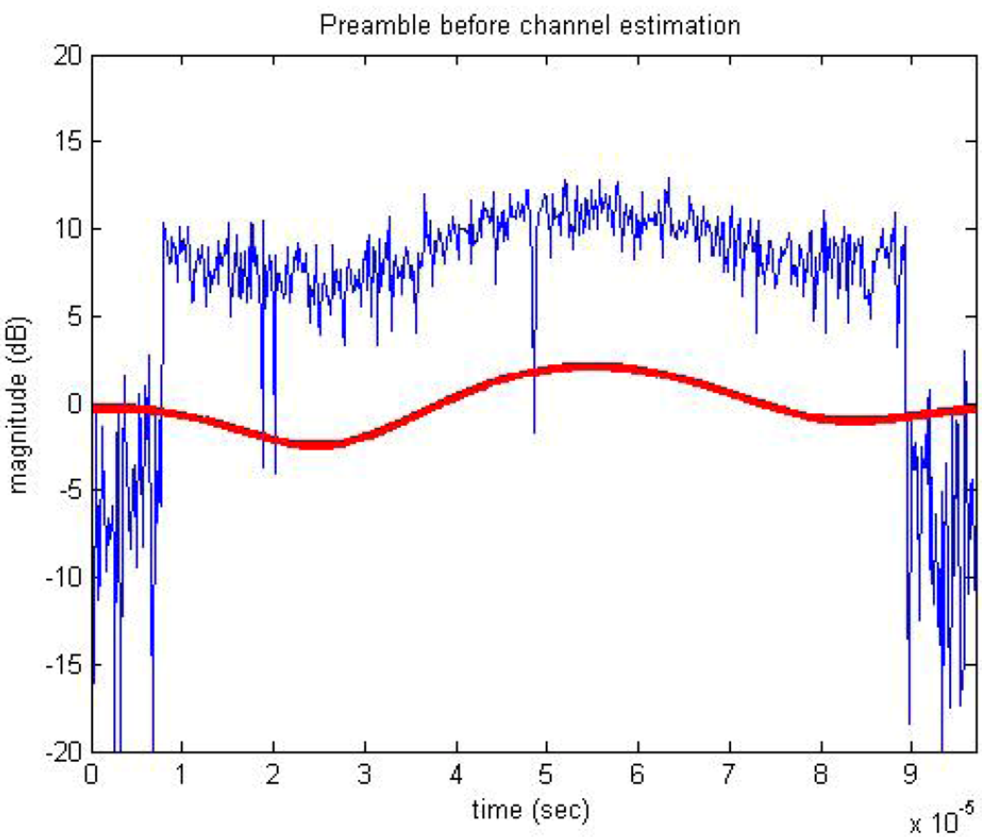

Figure 23: *Preamble before channel estimate applied*

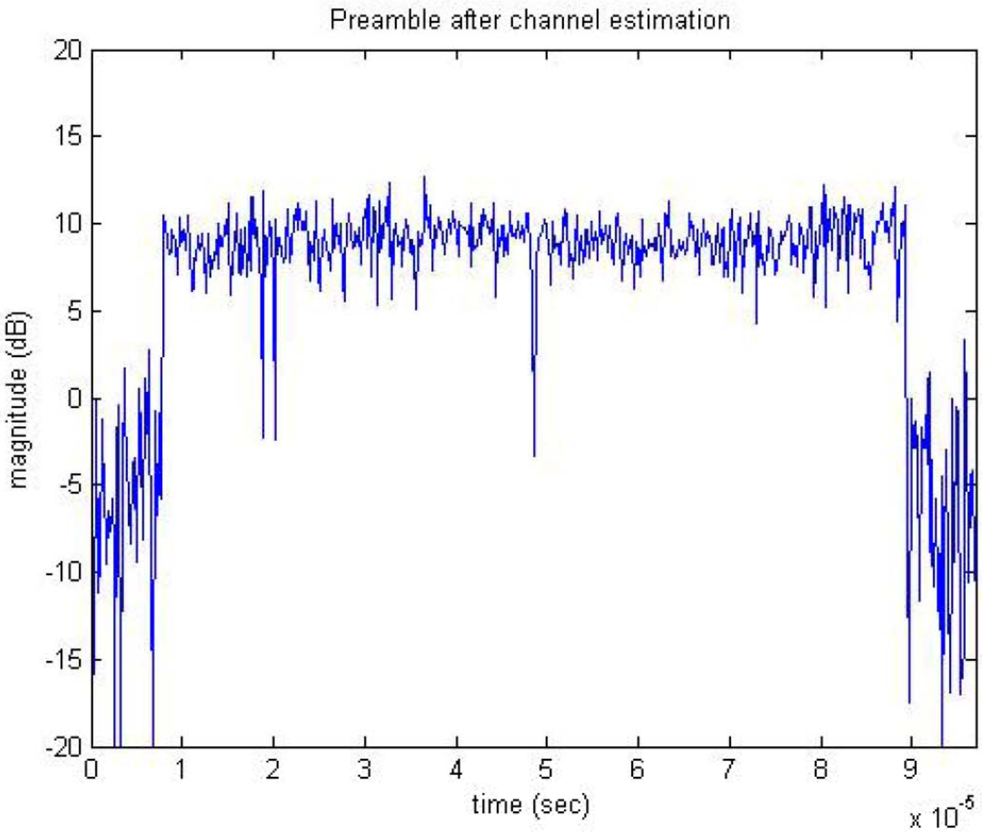

Figure 24: *Preamble after channel estimate applied*

3.3.3 Program execution

The simulation is executed by calling the *wimax.m* function. The simulation can be set to various debugging levels ranging from 0 to 2. As the debugging level is increased, more descriptive output status messages are displayed. The following is an example output of a simulation run with debugging level set to the highest level.

```
Bandwidth: 5 MHz
Cyclic prefix: 0.0625
SUI channel: 1
SNR: 15 dB
Preamble threshold: 6 dB

Generating fading channel..
   resetting channel 86 times
   path gains: 0.8059-0.2213i -0.06057-0.11847i 0.020055+0.015404i

Generating MAC DL MAP message..
   MAC DL MAP message length: 544-bits (68-bytes)

   msg_type: 2
   frame duration code: 4
   frame number: 1128
   DCD count: 0
   BSID: 0xDEADBEEF
   no OFDMA symbols: 24

   DIUC: 0
      N_CID assigned: 4
      CID: 0xA10C
      CID: 0xB28F
      CID: 0xC30C
      CID: 0xD99F
      symbol offset: 10
      subchan offset: 1
      boosting: 0
      symbol count: 10
      subchan count: 5
      repetition code: 0
   DIUC: 1
      N_CID assigned: 2
      CID: 0xA10C
      CID: 0xB28F
      symbol offset: 20
      subchan offset: 1
      boosting: 0
      symbol count: 14
      subchan count: 5
      repetition code: 0
   DIUC: 2
      N_CID assigned: 2
      CID: 0xC30C
      CID: 0xD99F
      symbol offset: 10
      subchan offset: 6
      boosting: 0
      symbol count: 14
      subchan count: 5
      repetition code: 0
   DIUC: 3
      N_CID assigned: 1
      CID: 0xA10C
```

symbol offset: 24
subchan offset: 6
boosting: 0
symbol count: 10
subchan count: 5
repetition code: 0
DIUC: 4
N_CID assigned: 1
CID: 0xB28F
symbol offset: 10
subchan offset: 11
boosting: 0
symbol count: 18
subchan count: 5
repetition code: 0
DIUC: 5
N_CID assigned: 1
CID: 0xC30C
symbol offset: 28
subchan offset: 11
boosting: 0
symbol count: 6
subchan count: 5
repetition code: 0

Encoding and modulating MAC DL MAP message..
randomized data: (68-bytes) 0xFB3216B0...
encoded data: (136-bytes) 0xE6B8DCF3...
interleaved data: (136-bytes) 0xE186777E...
modulated data: (544-symbols) -0.70711-0.70711i -0.70711+0.70711i 0.70711+0.70711i...

Creating mapping matrix..
DL burst no: 1 DIUC: 0 FEC code type: QPSK(CC)1/2
DL burst no: 2 DIUC: 1 FEC code type: QPSK(CC)3/4
DL burst no: 3 DIUC: 2 FEC code type: 16-QAM(CC)1/2
DL burst no: 4 DIUC: 3 FEC code type: 16-QAM(CC)3/4
DL burst no: 5 DIUC: 4 FEC code type: 64-QAM(CC)1/2
DL burst no: 6 DIUC: 5 FEC code type: 64-QAM(CC)2/3

Generating random data for each DL burst..
entry data 1: 0xAD32F871E9F276EF...
entry data 2: 0xCE7C0A69351C7B06...
entry data 3: 0x9F94E9202617EE36...
entry data 4: 0x5291665E2A0E8DAC...
entry data 5: 0x0EF41AC77A7E5A4A...
entry data 6: 0x073777781574BFC4...

Calculating UBS for each DL burst..
DL burst no: 1
DL burst sequence: QPSK(CC)1/2
total slots available: 25
total concatenated slots: 25
coding bits per subcarrier: 2
uncoded blk size (UBS): 150 (bytes)

DL burst no: 2
DL burst sequence: QPSK(CC)3/4
total slots available: 35
total concatenated slots: 35
coding bits per subcarrier: 2
uncoded blk size (UBS): 315 (bytes)

DL burst no: 3
DL burst sequence: 16-QAM(CC)1/2

total slots available: 35
total concatenated slots: 35
coding bits per subcarrier: 4
uncoded blk size (UBS): 420 (bytes)

DL burst no: 4
DL burst sequence: 16-QAM(CC)3/4
total slots available: 25
total concatenated slots: 25
coding bits per subcarrier: 4
uncoded blk size (UBS): 450 (bytes)

DL burst no: 5
DL burst sequence: 64-QAM(CC)1/2
total slots available: 45
total concatenated slots: 45
coding bits per subcarrier: 6
uncoded blk size (UBS): 810 (bytes)

DL burst no: 6
DL burst sequence: 64-QAM(CC)2/3
total slots available: 15
total concatenated slots: 15
coding bits per subcarrier: 6
uncoded blk size (UBS): 360 (bytes)

Encoding and modulating data for each DL burst..
transmit data: (150-bytes) 0xAD32F871...
randomized data: (150-bytes) 0x5404EEC5...
encoded data: (300-bytes) 0x34807B37...
interleaved data: (300-bytes) 0x0674CEC7...
modulated data: (1200-symbols) 0.70711+0.70711i 0.70711+0.70711i 0.70711-0.70711i...

transmit data: (315-bytes) 0xCE7C0A69...
randomized data: (315-bytes) 0x374A1CDD...
encoded data: (420-bytes) 0x196156E6...
interleaved data: (420-bytes) 0x268755E8...
modulated data: (1680-symbols) 0.70711+0.70711i -0.70711+0.70711i 0.70711-0.70711i...

transmit data: (420-bytes) 0x9F94E920...
randomized data: (420-bytes) 0x66A2FF94...
encoded data: (840-bytes) 0x3A032B13...
interleaved data: (840-bytes) 0x30A69466...
modulated data: (1680-symbols) 0.31623-0.94868i 0.31623+0.31623i -0.31623-0.31623i...

transmit data: (450-bytes) 0x5291665E...
randomized data: (450-bytes) 0xABA770EA...
encoded data: (600-bytes) 0xE8FCADCE...
interleaved data: (600-bytes) 0xFA4FDBD7...
modulated data: (1200-symbols) -0.94868-0.94868i -0.31623-0.31623i 0.94868+0.31623i...

transmit data: (810-bytes) 0x0EF41AC7...
randomized data: (810-bytes) 0xF7C20C73...
encoded data: (1620-bytes) 0xE650DD9A...
interleaved data: (1620-bytes) 0xF9A0CE6E...
modulated data: (2160-symbols) -1.0801-0.77152i 1.0801+0.77152i 0.46291+1.0801i...

transmit data: (360-bytes) 0x07377778...
randomized data: (360-bytes) 0xFE0161CC...
encoded data: (540-bytes) 0xCA64F14A...
interleaved data: (540-bytes) 0xD56B08E9...
modulated data: (720-symbols) -0.77152-0.1543i 0.77152-0.77152i -0.1543-0.46291i...

Generating and mapping preamble to DL subframe..

```
    Generating preamble for IDCells: 1 3 28
    PN series: (seg 0 IDCell 1) 0xD8C30DA5...
    PN series: (seg 1 IDCell 3) 0xB027CB82...
    PN series: (seg 2 IDCell 28) 0x89B93046...

Generating and processing FCH..
    used subchan bitmap: 1 1 1 1 1 1
    repetition code: 0
    coding type: 0
    DL MAP length: 12 slots

Mapping FCH to DL subframe..
Mapping DL MAP to DL subframe..
Mapping data to DL subframe..
Transmitting DL subframe..

Processing receive buffer..
    receive buffer points > 6-dB: 415
    NFFT: 512 points

Performing preamble-based channel estimation..
Extracting cell IDs from preamble..
    segment: 0 IDCell: 1
    segment: 1 IDCell: 3
    segment: 2 IDCell: 28

Extracting FCH..
    used subchan bitmap: 1 1 1 1 1 1
    repetition code: 0
    coding type: 0
    DL MAP length: 12 slots
```

3.3.4 Simulation results

On review of the output messages shown in the previous section, the preamble was successfully extracted from the receive buffer and used to determine the FFT size. In this simulation example a bandwidth of 5.0-MHz was used and the FFT size was found to be 512-points. In other cases, the model will correctly determine the FFT size (128, 1024 or 2048 points) for the given bandwidth. After the preamble-based channel estimation step, the correct cell IDs were extracted from the preamble. The content of the frame control header were also correctly extracted from the second and third OFDMA symbols.

The simulation is only partially complete as the DL MAP and data streams are not extracted from the transmitted frame at this time. The simulation model confirms that performance is strongly dependent on the channel characteristics. For a given SUI channel, the preamble is successfully decoded only if the SNR is above a certain minimum value. For SUI channel 1 (flat terrain with light scatterer density) this threshold is approximately 10-dB. For higher SUI channel numbers with increasing scatterer densities the minimum SNR must be increased.

4 Conclusion

During the 6-month period from 14 April to 14 November, 2008, five separate simulation models of the WiMAX PHY layer were produced with increasing complexity. The first version (V1) modeled a fixed WiMAX PHY layer based on the original IEEE802.16-2004 standard. The first model was based on existing Matlab code in order to speed up development and gain fast understanding of the basic concepts involved. Important lessons were learned that were applied to consecutive simulation versions.

During the second phase of development two software versions were produced. Version 2 was an interim version. The third version (V3) of the simulation expanded on the original model and incorporated several changes and corrections. The third version was also based on a fixed WiMAX PHY layer and investigated the channel effects on the quality of a transmitted image. During development the focus was on understanding the differences between the fixed and mobile WiMAX PHY layer as described by the IEEE802.16e-2005 amendment to the original standard. A major improvement to the third version was the incorporation of an accurate channel estimation algorithm.

The first three simulation versions were basically an introduction to the key concepts and technologies used in the implementation of the WiMAX PHY layer. All of the lessons learned were essential to the development of a mobile WiMAX PHY layer simulation completed during the third phase. During the third phase of development two software versions were produced. Version 4 was an interim version. Although the final version (V5) is incomplete, it employs concepts basic to mobile WiMAX such as scalable OFDMA, subcarrier permutation modes, sectorization, frame generation and preamble-based channel estimation techniques. Version 5 models the downlink and contains limited modeling of the MAC layer.

An important conclusion drawn from the V5 model is the susceptibility of the physical layer to channel quality. As the receiver must first successfully capture, extract and decode the transmitted frame preamble and other control messages, the simulation performance is heavily dependent on the channel's fading characteristics and random noise introduced into the channel. Future simulation versions will focus on testing and evaluating system performance in various fading environments and operating modes.

The complete simulation model of the mobile WiMAX layer is far from complete. Future simulation version will incorporate other concepts such as adaptive modulation and coding (AMC), multiple-input multiple-output (MIMO), and will simulate the uplink.

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This report details and summarizes the work performed in developing computer simulation models for fixed and mobile WiMAX physical layers. The development was divided into 3 phases during which various simulation models of increasing complexity were produced. The models were coded using Matlab software. Emphasis was placed on developing source code in strict accordance with WiMAX standard specifications.

The initial software models simulated a fixed WiMAX physical layer during which key concepts and technologies were investigated. The software models developed during the last phase provided a partial simulation of a mobile WiMAX physical layer. An excellent understanding was gained of mobile WiMAX technology and its limitations in a simulated environment. Simulations showed that the performance of the WiMAX physical layer is dependent strongly on the propagation channel through which the RF signals propagate.

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